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# FINDINGS OF A RECENT ORNL REVIEW OF DOSIMETRY FOR THE JAPANESE ATOMIC-BOMB SURVIVORS

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OAK RIDGE NATIONAL LABORATORY
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# FINDINGS OF A RECENT ORNL REVIEW OF DOSIMETRY FOR THE JAPANESE ATOMIC-BOMB SURVIVORS

George D. Kerr

## ABSTRACT

More detail than previously available on the leakage spectra of neutrons from the Nagasaki and Hiroshima weapons was provided by calculations made at the Los Alamos National Laboratory in 1976. Several neutron-transport calculations using these data predicted significantly less neutron exposure in Hiroshima than the current radiation-exposure estimates for survivors designated as T65D (or Tentative 1965 Doses). The difference was extremely important since recent studies using the T65D estimates have predicted a very large leukemia risk for neutrons at low exposure levels in Hiroshima.

A review of the dosimetry for the atomic-bomb survivors, requested by the National Council on Radiation Protection through the U.S. Department of Energy, was started in late 1979. Several early studies aimed at resolving the discrepancies gave ambiguous results. This was especially true of sulfur activation by fast neutrons which was more easily related to neutron leakage from the weapons and to neutron exposure of the survivors than thermal neutron activation of other materials. A breakthrough was provided in mid-1980 by information on sulfur activation found in a Japanese report on radiation surveys made in the two cities immediately after the bombings. This information quickly resolved many of the ambiguities between the newer neutron-transport calculations and the older T65D estimates.

Some findings of the review are that the neutron exposures in Hiroshima were probably less than the T65D estimates by factors varying from about four at a ground distance of 1000 m to eight at 2000 m, and the gamma-ray exposures were greater than the T65D estimates starting at about 1000 m and were probably larger by a factor of about three at 2000 m. In Nagasaki, the situation was reversed with respect to gamma rays, and the T65D estimates were higher, but the differences were small (i.e., about 20% at 1000 m and 30% at 2000 m). As a result, it now appears that leukemia and other late effects at lower exposure levels in Hiroshima were due largely to gamma rays rather than neutrons. This may not be true at higher exposure levels in Hiroshima, however.

Any reanalysis of data on late effects among the atomic-bomb survivors should be regarded as highly speculative until some other important issues have been investigated in more detail. These issues include the anisotropy in neutron leakage from the Hiroshima weapon, the energy yield of the Hiroshima weapon, the shielding factors for houses, and the organ-dose factors for the atomic-bomb survivors.

# INTRODUCTION

The epidemiological studies of the atomic-bomb survivors by the Radiation Effects Research Foundation (RERF), formerly the Atomic Bomb Casualty Commission (ABCC), provide invaluable quantitative data on the late effects of radiation exposure (National Academy of Sciences, 1980; United Nations, 1980). Because of the importance attached to these data in the assessment of radiation exposure risks, an up-to-date review of the dosimetry for the atomic-bomb survivors was recently requested by the National Council on Radiation Protection (NCRP) through the U.S. Department of Energy. The expert assistance of others in the review has been provided at the request of the NCRP by both the U.S. Department of Energy (DOE) and the U.S. Defense Nuclear Agency (DNA).

A primary objective of the review was to determine whether the large leukemia risk for neutrons found at low exposure levels in Hiroshima by Rossi and Mays (1978) and by Ishimaru et al. (1979) was real or whether it was the result of a bias in the current radiation-exposure estimates for survivors designated as T65D (or Tentative 1965 Doses) (Auxier, 1977). The potential for a bias existed because the two weapons dropped in Japan were of entirely different design, content, and construction (Brown and MacDonald, 1977; Groueff, 1967). Some radiation-exposure data were available from test firings of Nagasaki-type weapons, but the Hiroshima-type weapon was never fired outside the one combat drop in Japan.

The Hiroshima weapon, code named Little Boy, was a massive gun-assembly device (see Fig. 1) which used a small propellant charge to shoot one piece of $^{235}U$ down a barrel into a second piece to form a critical mass at the time of explosion (ATE) (Glasstone and Dolan, 1977; Thomas and Witts, 1977). This weapon was exploded about 8:15 AM on August 6, 1945, over the center of the city (see Fig. 2) at a height of 580 m or 1900 feet (Hubbell et al., 1969; Hiroshima and Nagasaki Cities, 1981). The Nagasaki weapon, code named Fat Man, was an implosion-type device (see Fig. 1) which used thick charges of high explosive (HE) to compress a subcritical mass of $^{239}Pu$ (and a tamper of $^{238}U$) into a

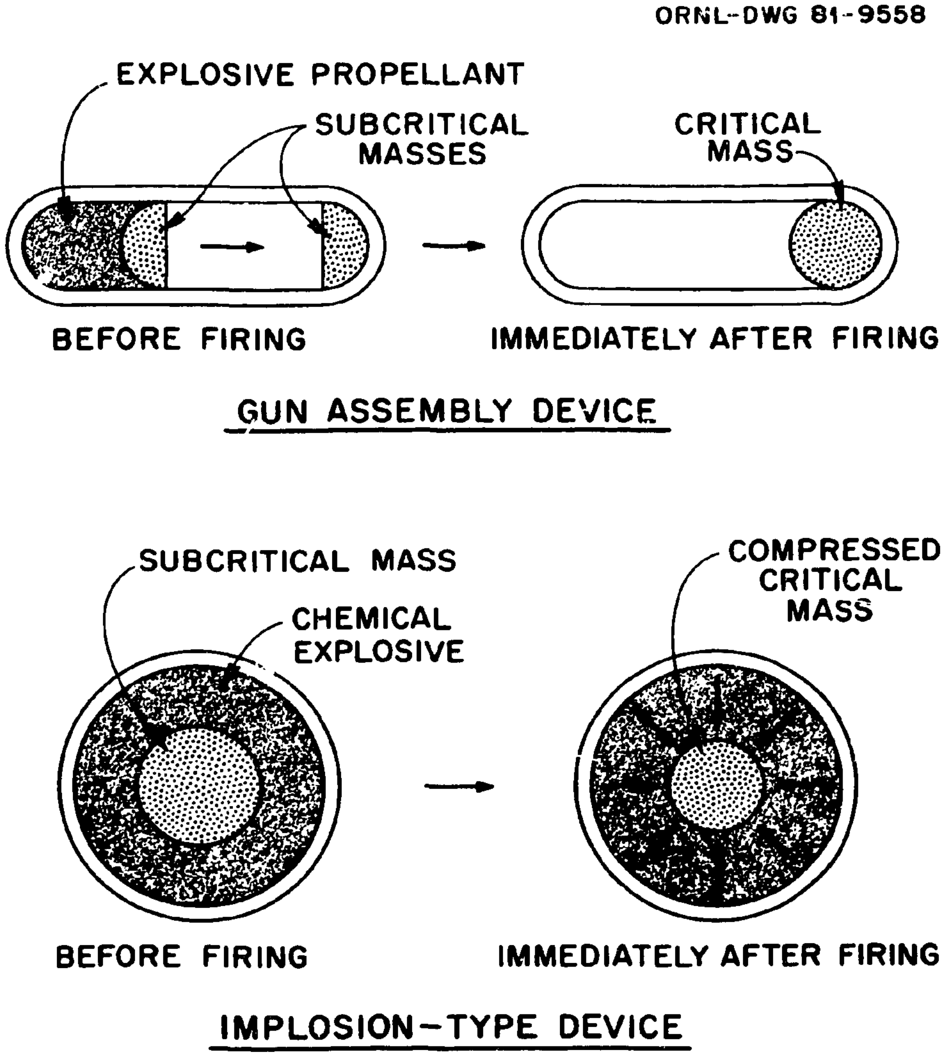


Fig. 1. Schematic illustrating the principle of a gun-assembly device (top) and implosion-type device (bottom) (Glasstone and Dolan, 1977).

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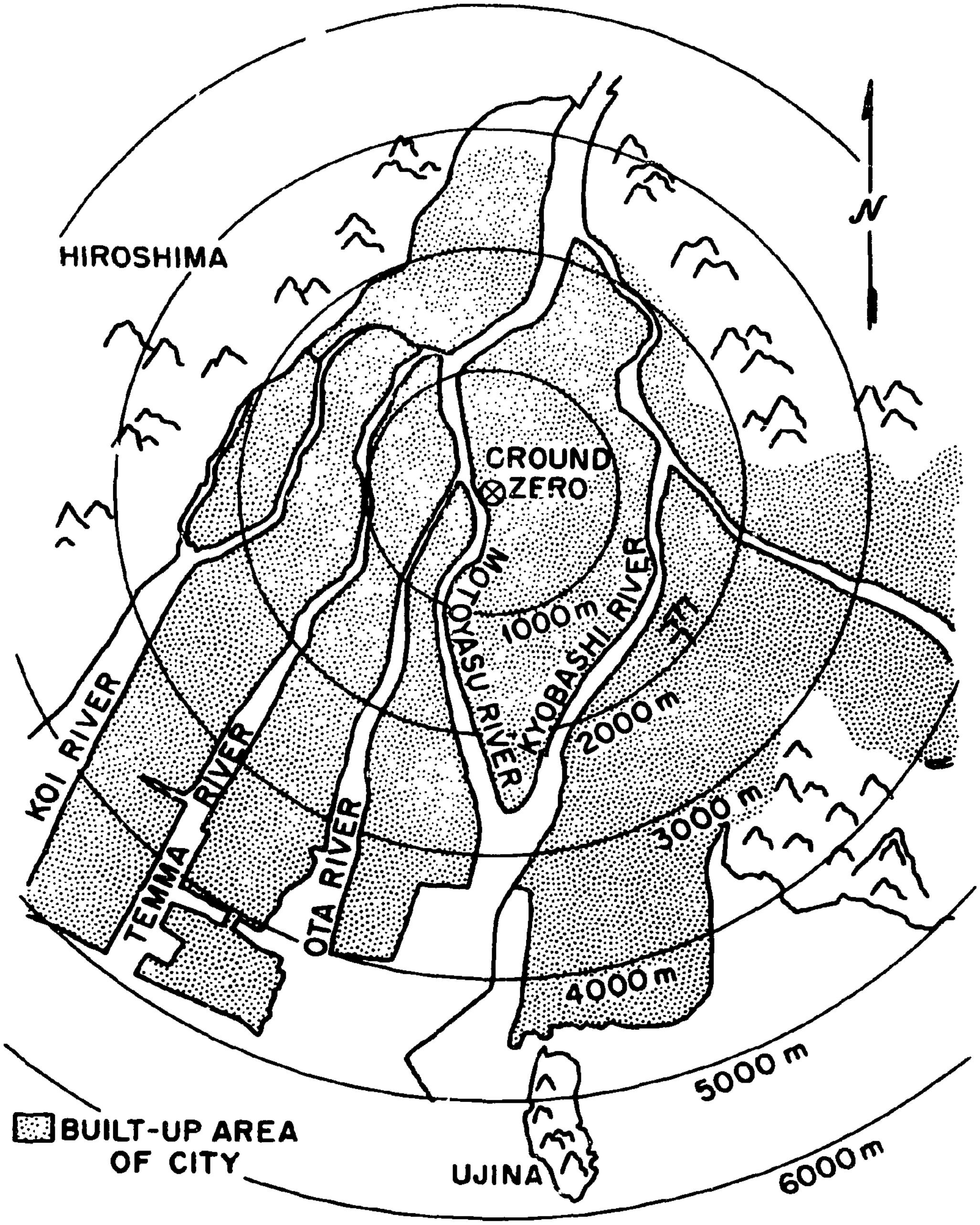


Fig. 2. Map showing built-up areas and location of ground zero in Hiroshima.

critical mass ATE (Glasstone and Dolan, 1977; Lamont, 1965). It was exploded about 11:02 AM on August 9, 1945, over the Urakami Valley in the northern part of the city (see Fig. 3) at a height of 503 m or 1650 feet (Kerr and Solomon, 1976; Hiroshima and Nagasaki Cities, 1981).

The radiation exposure decreases rapidly with increasing distance from the burst point of a weapon due in part to geometrical attenuation and in part to atmospheric attenuation (Abbott, 1973). Thus, one important parameter in the estimation of a survivor's radiation exposure is distance from the burst point (or air-zero point) of the weapon (see Fig. 4). The distance R from air zero in the case of a flat ground surface is given by the square root of $d^2 + H^2$ where H is the weapon's burst height and d is the survivor's distance from ground zero. If the terrain near ground zero is uneven, as in Nagasaki, then the slant distance R is equal to the square root of $d^2 + (H - h)^2$ where h is the survivor's elevation relative to ground zero. Shielding by uneven terrain and surrounding structures are other important parameters that must be taken into account in estimating a survivor's radiation exposure (see Fig. 5) (Arakawa, 1960). The structural shielding conditions reported by survivors who were close to ground zero ATE are broken down into several categories in Table 1 (Kerr, 1979a; Davis et al., 1966).

## TENTATIVE 1965 DOSES

Most of the survivors were exposed inside residential wood-frame structures (see Table 1), and the uniformity of Japanese house construction made a definitive dosimetry study feasible (Noble, 1968; Auxier, 1977). The current radiation-exposure estimates take into account a survivor's shielding by surrounding structures primarily through the house-shielding factors developed by Cheka et al. (1965), and a survivor's distance from ground zero through the tissue kerma vs distance relationships developed by Auxier et al. (Oak Ridge National Laboratory, 1965b; Auxier et al., 1966). These estimates are designated as T65D (Milton and Shohoji, 1968) to distinguish them from some earlier radiation-exposure estimates for survivors designated as T57D (or Tentative 1957

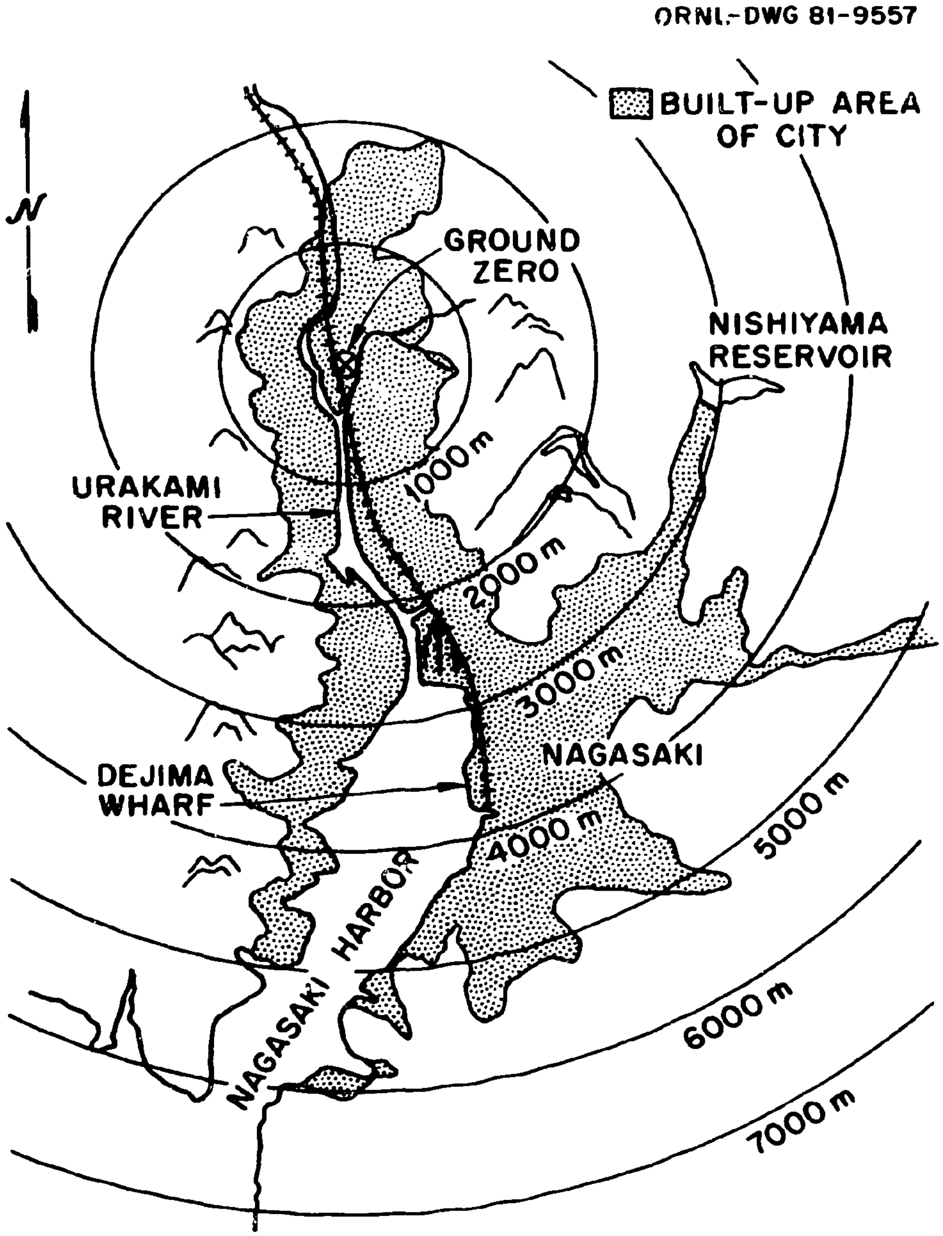


Fig. 3. Map showing built-up areas and location of ground zero in Nagasaki.

ORNL-DWG 81-9559

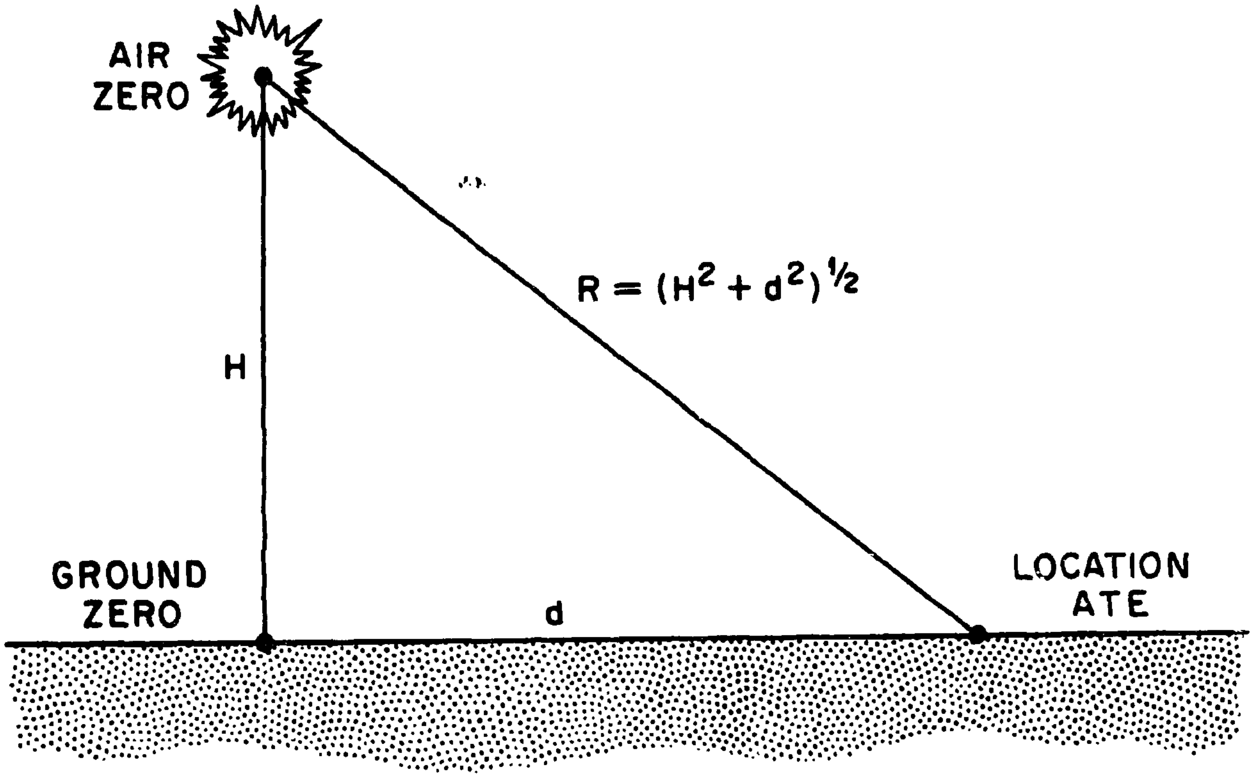


Fig. 4. Schematic illustrating the relationship between the height of burst H above ground, the survivor's distance d from ground zero, and the slant distance R from the burst point or air-zero point of the weapon.

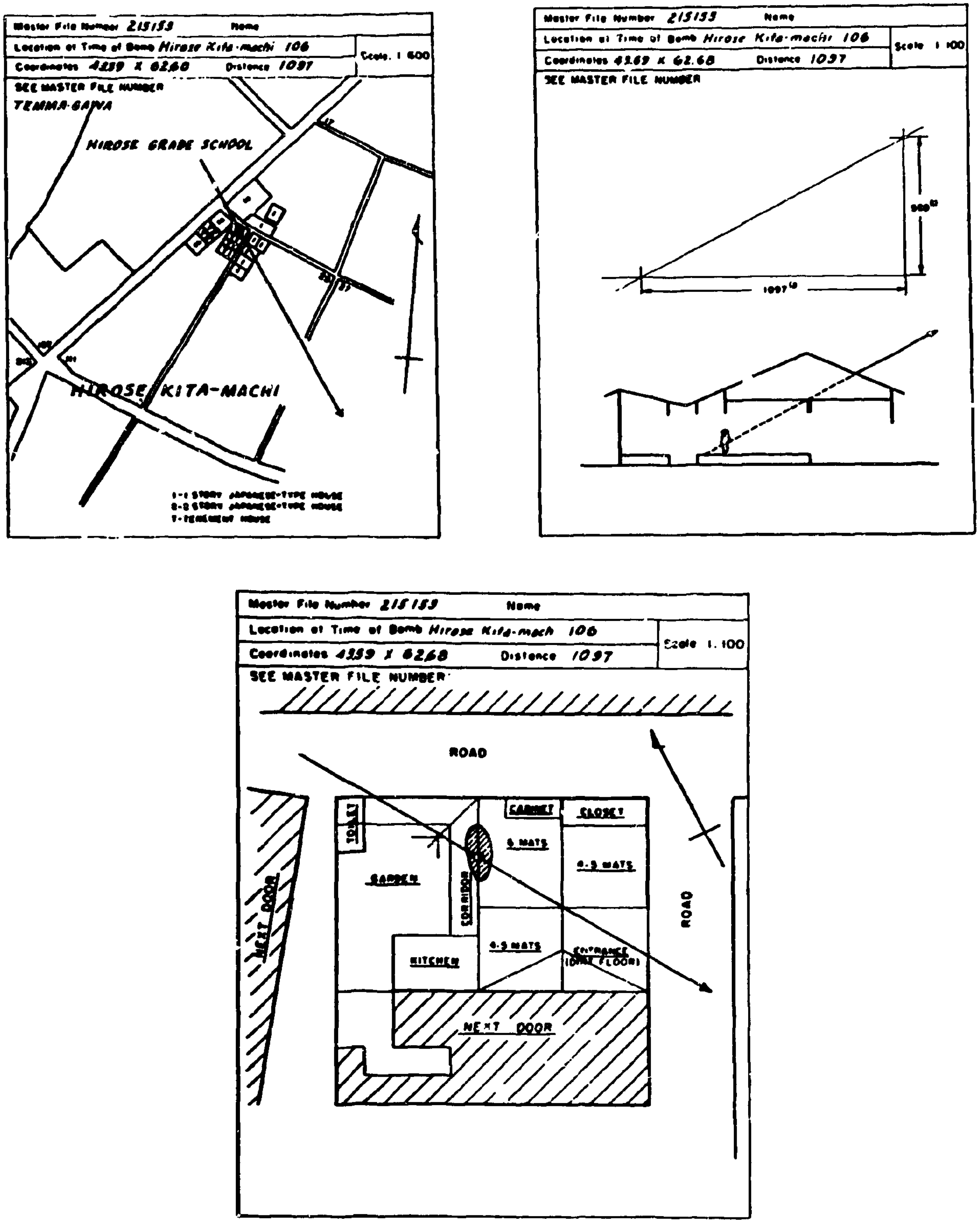


Fig. 5. Example of a shielding history on a survivor located inside a house at time of explosion (Arakawa, 1960).

Table 1. Approximate percentage of survivors reporting various exposure conditions at distances less than 1600 m from ground zero in Hiroshima and 2000 m from ground zero in Nagasaki

| Exposure conditions | Percentage of Hiroshima survivors | Percentage of Nagasaki survivors |
|---|---|---|
| Outdoors | | |
| Unshielded | 10 | 5 |
| Shielded | 10 | 10 |
| Indoors | | |
| Wooden frame structures | 75 | 65 |
| Concrete and other structures | 5[a] | 20[b] |

[a]Mostly heavy concrete or brick buildings.

[b]About half heavy concrete buildings, and about half light industrial steelframe buildings either at the Steel and Arms Works south of ground zero or at the Ordnance and Torpedo Plant north of ground zero.

Doses) (Arakawa, 1960; Ritchie and Hurst, 1959; York, 1957). In the case of the Fat Man device, some radiation-exposure data were available from weapon tests, and these data were used in constructing the T65D tissue kerma vs distance relationships for Nagasaki. Several duplicate Fat Man devices were fired during the Trinity test in July 1945 and the Crossroads Able and Baker tests in 1946 (Wilson, 1956; Auxier, 1977), and results of these tests indicate the energy yield of the Nagasaki weapon was equivalent to 22 (±2) kilotons (or kton) of TNT (Malik, 1954; 1980).

There were no data from weapon tests in the case of Little Boy, and the T65D tissue kerma vs distance relationships for Hiroshima were constructed by using data from several of the most nearly appropriate weapon tests and data from reactor experiments (Oak Ridge National Laboratory, 1965b; Auxier et al., 1966). One reactor experiment at Los Alamos National Laboratory (LANL) using the Ichiban Critical Assembly provided data on neutron leakage from Little Boy (Oak Ridge National Laboratory, 1965a; Thorngate et al., 1966), and another reactor experiment at the Nevada Test Site (NTS) using the ORNL Health Physics Research Reactor (HPRR) provided data on the penetration of neutrons (and gamma rays) in an air-over-ground geometry (Haywood et al., 1964; Haywood, 1965). The resulting tissue kerma vs distance relationships were normalized to an estimated energy yield of 12.5 (±2.5) kton for the Hiroshima weapon. Later studies by Lord Penney et al. (1968; 1970) and by Auxier et al. (Oak Ridge National Laboratory, 1968; Auxier, 1977) reduced the estimated probable error to ±10% (or about 1 kton).

The T65D tissue kerma vs distance relationships were found to agree in general with results of independent studies by Hashizume et al. (1967) of the Japanese National Institute of Radiological Sciences (JNIRS) and Ichikawa et al. (1966) of the University of Kyoto, Japan (see Fig. 6). The gamma-ray exposure at various ground distances in both Hiroshima and Nagasaki were estimated by Ichikawa et al. (1966) using thermoluminscence of the crystalline component from roof tiles. Some rather large uncertainities were involved in the distance estimates of their study (Hashizume et al., 1967). Since roof tiles were used

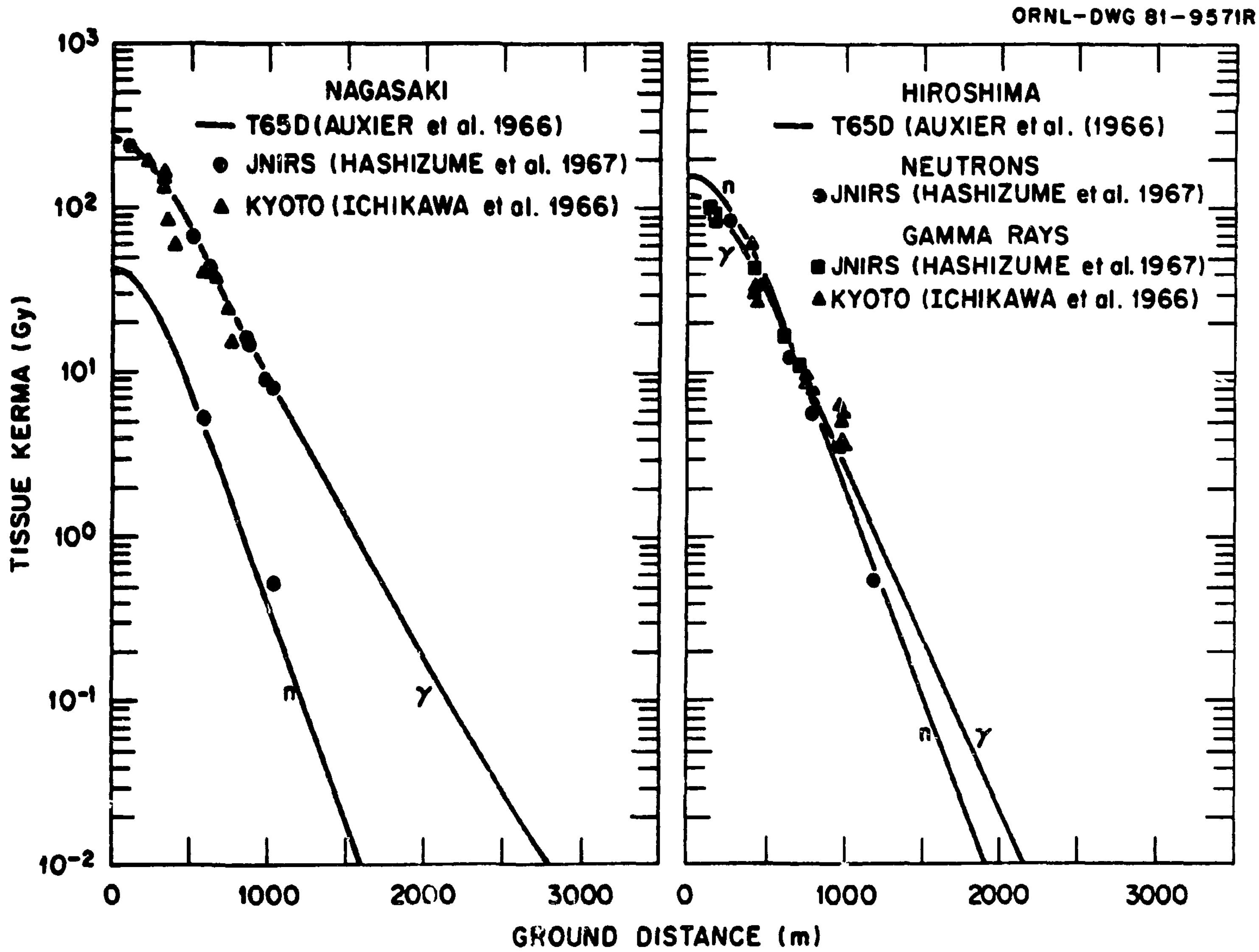


Fig. 6. Comparison of T65D tissue kerma vs distance relationships with data from Japanese dosimetry studies (Auxier, 1977).

only on Japanese houses and all houses close to ground zero were destroyed, the exact location of each roof-tile sample ATE was in doubt. The estimates of gamma-ray and neutron exposure in the JNIRS study by Hashizume et al. (1967) were derived from measurements of the gamma-induced thermoluminescence in decorative-tile and brick samples and neutron-induced $^{60}Co$ radioactivity in steel reinforcing-rod samples taken from commercial buildings that had been repaired and used for a number of years after the bombings. Thus, the exact location of each sample ATE was well known, and the uncertainty in the ground distance was minimized. The JNIRS study seemed to confirm the T65D study (Auxier, 1975; Hashizume and Maruyama, 1975a), and the T65D estimates of a survivor's radiation exposure were used with a great deal of confidence until recently.

## NEUTRON LEAKAGE DATA

A letter was circulated in 1976 by Preeg of LANL which gave more detail than previously available on the leakage spectra of neutrons (and gamma rays) from the Fat Man and Little Boy devices (see Tables 2 and 3) (Preeg, 1976). Included in the letter were the results of some additional calculations of neutron penetration in an infinite air medium using the HEART computer code which predicted significantly less neutron exposure in Hiroshima per unit energy yield of Little Boy than the T65D estimates. This was also found to be the case in more realistic air-over-ground calculations in 1977 by Kaul and Jarka of Science Applications, Inc. (SAI) using the ATR4 computer code (Kaul and Jarka, 1977) and by J. Pace of ORNL using the DOT computer code (J. Pace, 1977). Some troublesome discrepancies existed in the air-over-ground calculations, however. It was shown in 1979 by J. Pace of ORNL that the moisture content of the air was an extremely important parameter in the calculations for Little Boy (see Fig. 7) (J. Pace, 1979). Kaul and Jarka had used a dry NTS-type air in their 1977 calculations, while J. Pace in his 1977 calculations had used a moist air composition derived from data on atmospheric conditions existing ATE in Hiroshima (Malik,

Table 2. Leakage spectra of neutrons from the Little Boy and Fat Man devices as calculated by Preeg (1976)

| Energy interval (MeV) | Neutron leakage (n kton$^{-1}$) | |
|---|---|---|
| | Little Boy | Fat Man |
| 6.07 E+0 to 7.79 E+0[a] | 9.54 E+19 | 5.34 E+19 |
| 3.68 E+0 to 6.07 E+0 | 3.65 E+20 | 1.10 E+20 |
| 2.865 E+0 to 3.68 E+0 | 4.39 E+20 | 8.84 E+19 |
| 2.232 E+0 to 2.865 E+0 | 7.79 E+20 | 1.51 E+20 |
| 1.738 E+0 to 2.232 E+0 | 1.21 E+21 | 1.19 E+20 |
| 1.353 E+0 to 1.738 E+0 | 1.54 E+21 | 1.14 E+20 |
| 8.23 E-1 to 1.353 E+0 | 5.18 E+21 | 2.37 E+20 |
| 5.00 E-1 to 8.23 E-1 | 1.19 E+22 | 1.66 E+20 |
| 3.03 E-1 to 5.00 E-1 | 1.85 E+22 | 7.91 E+19 |
| 1.84 E-1 to 3.03 E-1 | 1.65 E+22 | 8.15 E+19 |
| 6.76 E-2 to 1.84 E-1 | 2.77 E+22 | 9.88 E+19 |
| 2.48 E-2 to 6.76 E-2 | 1.18 E+22 | 4.98 E+19 |
| 9.12 E-3 to 2.48 E-2 | 1.81 E+22 | 5.30 E+19 |
| 3.35 E-3 to 9.12 E-3 | 3.98 E+21 | 6.35 E+19 |
| 1.235 E-3 to 3.35 E-3 | 3.21 E+21 | 6.83 E+19 |
| 4.54 E-4 to 1.235 E-3 | 2.11 E+21 | 1.69 E+22 |
| 1.67 E-4 to 4.54 E-4 | 5.74 E+20 | 6.10 E+22 |
| 6.14 E-5 to 1.67 E-4 | 1.69 E+20 | 5.30 E+22 |
| 2.26 E-5 to 6.14 E-5 | 3.76 E+19 | 2.66 E+22 |
| 8.32 E-6 to 2.26 E-5 | | 8.43 E+21 |
| 3.06 E-6 to 8.32 E-6 | | 2.25 E+21 |
| 1.13 E-6 to 3.06 E-6 | | 9.56 E+20 |
| 4.14 E-7 to 1.13 E-6 | | 6.18 E+19 |
| Total | 1.24 E+23 | 1.71 E+23 |

[a]Read as 6.07 x $10^0$ or 6.07, etc.

Table 3. Leakage spectra of gamma rays from the Little Boy and Fat Man devices as calculated by Preeg (1976)

| Energy interval (MeV) | Gamma-ray leakage (photons $kton^{-1}$) | |
|---|---|---|
| | Little Boy | Fat Man |
| 9.0 to 10.0 | 1.67 E+19[a] | 9.52 E+18 |
| 8.0 to 9.0 | 1.57 E+19 | 3.66 E+18 |
| 7.0 to 8.0 | 5.18 E+20 | 9.52 E+20 |
| 6.0 to 7.0 | 1.36 E+20 | 2.56 E+20 |
| 5.0 to 6.0 | 1.05 E+20 | 1.82 E+20 |
| 4.0 to 5.0 | 2.48 E+20 | 4.46 E+20 |
| 3.0 to 4.0 | 3.78 E+20 | 7.03 E+20 |
| 2.0 to 3.0 | 5.33 E+20 | 1.94 E+21 |
| 1.0 to 2.0 | 7.95 E+20 | 3.65 E+21 |
| 0.5 to 1.0 | 1.44 E+21 | 9.80 E+20 |
| 0.1 to 0.5 | 6.26 E+19 | 2.00 E+20 |
| Total | 4.25 E+21 | 9.32 E+21 |

[a]Read as 1.67 x $10^{19}$, etc.

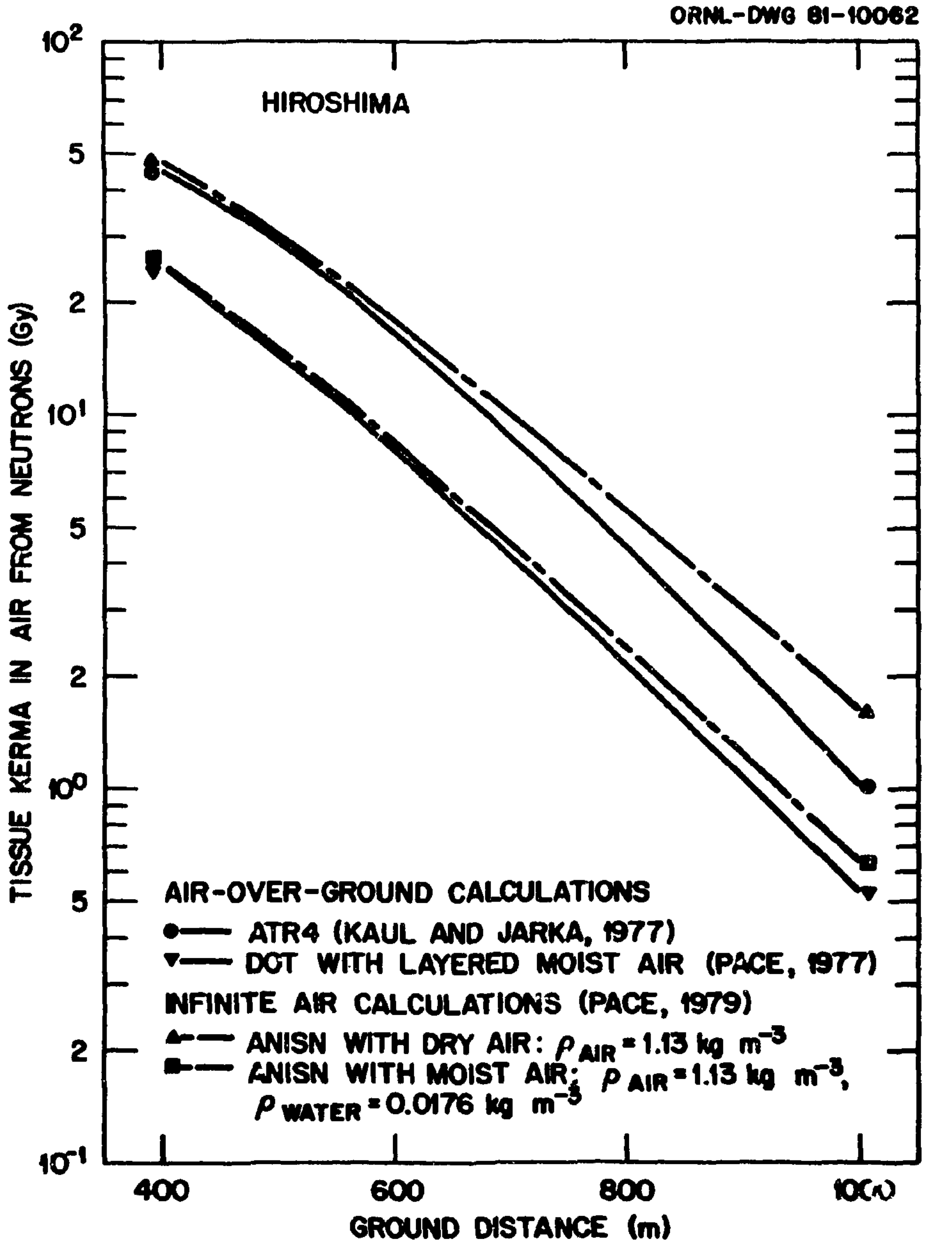


Fig. 7. Effect of moisture content in air on penetration of neutrons from Little Boy (J. Pace, 1979).

1976). A summary of atmospheric conditions ATE in both Hiroshima and Nagasaki is given in Table 4 (Malik, 1976; Kaul, 1981; Hiroshima and Nagasaki Cities, 1981).

One of the first investigations of this review started in 1979 was of data related to the neutron leakage from Little Boy and Fat Man (see Table 5) (Kerr, 1979b). The most recent data came, of course, from the Monte Carlo calculations by Preeg (1976). He used a spherically symmetric mockup of the weapons and a one-dimensional (1-D) hydro code which took into account the dynamic effect of weapon burnup on neutron (and gamma-ray) leakage from the weapons. The Little Boy device was cylindrically symmetric, and Preeg knew that the 1-D neutron-leakage calculation was approximate, but he thought in view of time and effort constraints that it would suffice (Marcum, 1978).

The T65D tissue kerma vs distance relationships in Hiroshima were constructed from neutron-leakage data obtained in 1964 studies using the Ichiban Critical Assembly at LANL (Oak Ridge National Laboratory, 1965b; Auxier et al., 1966). This was also a spherically symmetric mockup of the Little Boy device. A spherical core of highly enriched uranium was surrounded by spherical reflector and steel shells simulating the weapon's tamper and casing (Thorngate et al., 1966). The spherical design was used to simplify comparisons between experimental measurements and theoretical calculations. However, one LANL calculation, using Monte Carlo techniques, gave a value of 0.57 for the number of leakage neutrons per fission and another, using multigroup techniques, gave a value of 0.81 (Thorngate et al., 1966). This higher theoretical value was in good agreement with the experimental value obtained by ORNL (see Table 5). The ORNL measured value of 0.77 (or more precisely 0.766) fast neutron per fission and another ORNL measured value of $1.14 \times 10^{-11}$ Gy (1 gray or Gy = 100 rad) for the mean tissue kerma per unit fluence (n $cm^{-2}$) of fast neutrons having energies greater than 1 keV (Thorngate et al., 1966) gave

Table 4. Summary of atmospheric conditions in Hiroshima and Nagasaki ATE

| Parameter | Hiroshima | Nagasaki |
|---|---|---|
| Atmospheric pressure (millibar) | | |
| Ground zero[a] | 1018 | 1014 |
| Burst height[b] | 950 | 955 |
| Atmospheric temperature (°C) | | |
| Ground zero[a] | 26.7 | 28.8 |
| Burst height[b] | 23.0 | 25.6 |
| Relative humidity (%) | | |
| Ground zero[a] | 80 | 71 |
| Burst zero[b] | 71 | 67 |
| Dry air density (kg $m^{-3}$) | | |
| Ground zero[c] | 1.151 | 1.138 |
| Burst height[c] | 1.095 | 1.088 |
| Mean | 1.123 | 1.113 |
| Water vapor density (kg $m^{-3}$) | | |
| Ground zero[c] | 0.0203 | 0.0202 |
| Burst height[c] | 0.0146 | 0.0160 |
| Mean | 0.0174 | 0.0181 |
| Atmospheric density (kg $m^{-3}$) | | |
| Ground zero[c] | 1.171 | 1.158 |
| Burst height[c] | 1.110 | 1.104 |
| Mean | 1.140 | 1.131 |

[a]Surface weather data from the Hiroshima District Meteorological Observatory at 8:00 AM on August 6, 1945, and the Nagasaki Meteorological Observatory at 11:00 AM on August 9, 1945. See, for example, Hiroshima and Nagasaki Cities (1981).

[b]Estimates of atmospheric conditions at burst height from Malik (1976).

[c]Kaul (1981). Calculations using data on pages F-6 to F-8, D-94, and E-7 to E-12 of the *Handbook of Chemistry and Physics* (Weast, 1965).

Table 5. Summary of data on fast neutron and total neutron leakage from several devices

| Device | Type of investigation | Total neutron leakage | | Fast neutron leakage[a] | |
|---|---|---|---|---|---|
| | | Neutron per fission | Neutron per fission neutron born[b] | Neutron per fission | Neutron per fission neutron born[b] |
| Ichiban Critical Assembly | LANL Monte Carlo calculation[c] | | | 0.57 | 0.23 |
| | ORNL experimental measurement[c] | | | 0.77 | 0.31 |
| | LANL multigroup calculation[c] | 0.81 | 0.33 | 0.79 | 0.32 |
| Little Boy | ORNL experimental measurement[d] | | | 0.75 | 0.30 |
| | LANL Monte Carlo calculation[e] | 0.86 | 0.35 | 0.84 | 0.34 |
| Fat Man | ORNL experimental measurement[d] | | | 0.003 | 0.0009 |
| | LANL Monte Carlo calculation[e] | 1.18 | 0.41 | 0.011 | 0.0036 |

[a] Neutrons with energies greater than 1 keV.

[b] Assumes that the average number of neutrons produced for each fission was 2.5 in the $^{235}U$ fueled Ichiban Critical Assembly or Little Boy device and 2.9 in the $^{239}Pu$ fueled Fat Man device.

[c] Thorngate et al. (1966).

[d] Oak Ridge National Laboratory (1969).

[e] Preeg (1976).

$$\frac{1}{4\pi} \times \left(1.45 \times 10^{23}\ \frac{\text{fission}}{\text{kton}}\right) \times \left(0.766\ \frac{\text{n}}{\text{fission}}\right)$$
$$\times \left(1.14 \times 10^{-11}\ \frac{\text{Gy cm}^2}{\text{n}}\right) \times \left(1 \times 10^{-2}\ \frac{\text{m}}{\text{cm}}\right)^2$$
$$= 1.00 \times 10^{7}\ \frac{\text{Gy m}^2}{\text{kton}} \qquad (1)$$

as the T65D neutron-leakage factor for the tissue kerma at the burst point of Little Boy (Auxier et al., 1966).

Additional neutron-leakage experiments using duplicate Little Boy and Fat Man devices were conducted by ORNL in 1968 at the Burlington Arsenal (Oak Ridge National Laboratory, 1969). These experiments were made possible by the increased availability of $^{252}$Cf, which produces spontaneous fission neutrons at a rate of about $2.34 \times 10^{12}$ n s$^{-1}$ gm$^{-1}$ of source material (Barker, 1969). It was determined from careful comparisons with neutron sources calibrated by the U.S. National Bureau of Standards that the neutron emission rate of the nominal 300-$\mu$gm source used in the measurements was $6.07 \times 10^{8}$ n s$^{-1}$ (Wagner and Shinpaugh, 1968). The Burlington Arsenal replaced the HE and the core components with polyethylene and depleted uranium, respectively, and provided small bores for centering the $^{252}$Cf source in the replacement cores of depleted uranium (see Figs. 8 and 9). A fast neutron-leakage value based on neutron flux measurements made at a radius of 2 m from the $^{252}$Cf source in the Little Boy device (see Fig. 10) is given in Table 6 (Kerr, 1979b). These data indicate a leakage of about 0.30 fast neutron per fission neutron born (or neutron from the $^{252}$Cf source) and 0.75 fast neutron per fission if it is assumed that 2.5 neutrons were produced on the average per fission in the $^{235}$U fueled Little Boy device (Murray, 1957). If it is further assumed that 2.9 neutrons were produced on the average per fission in the $^{239}$Pu fueled Fat Man device, then the 2-m neutron-flux measurements (see Fig. 11) indicate a leakage of about 0.0009 fast neutron per fission neutron born (or neutron from the $^{252}$Cf source) and 0.003 fast neutron per fission (Kerr, 1979b).

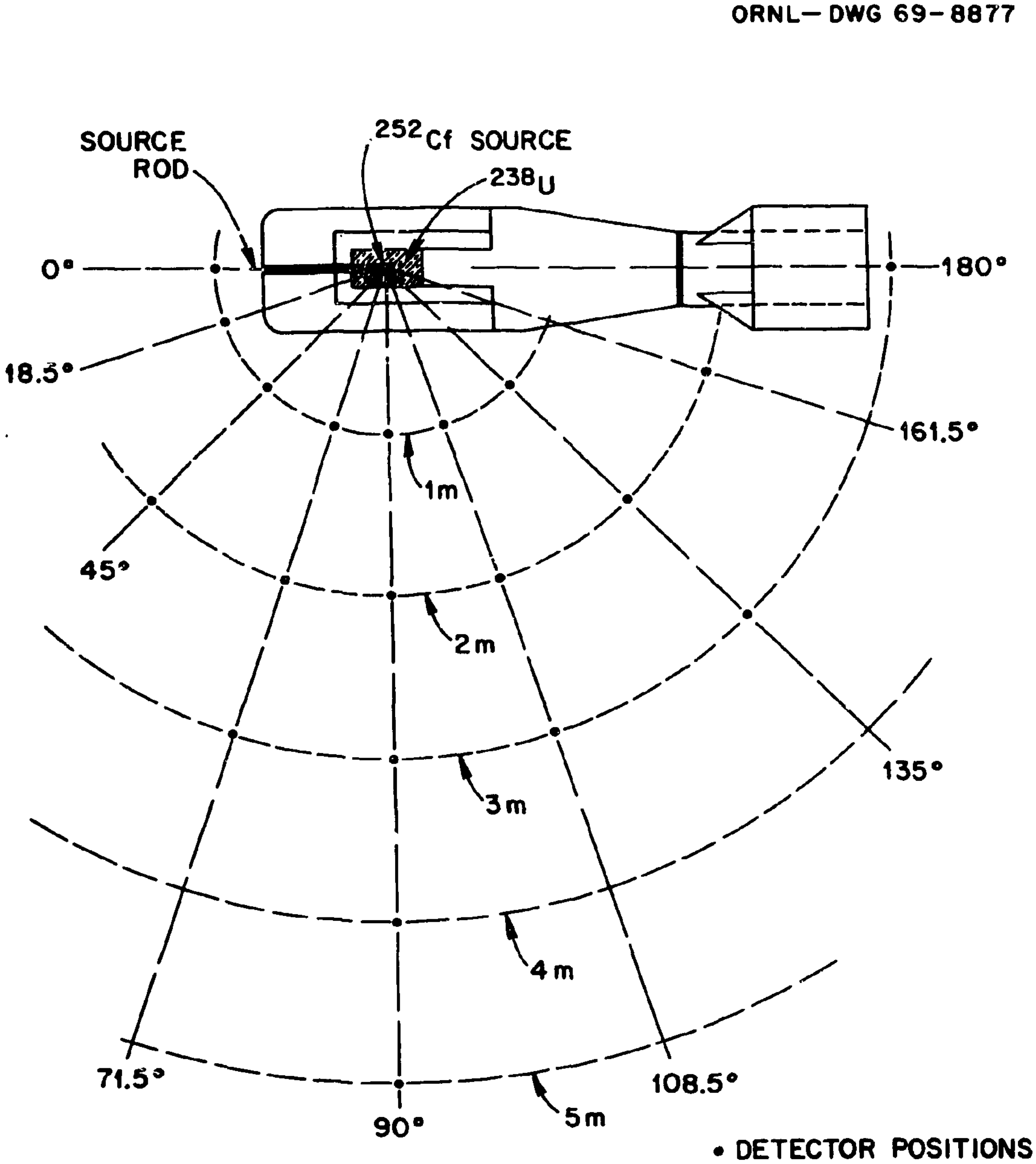


Fig. 8. Detector positions used in ORNL measurements of leakage radiation from Little Boy, looking down from above (Oak Ridge National Laboratory, 1969).

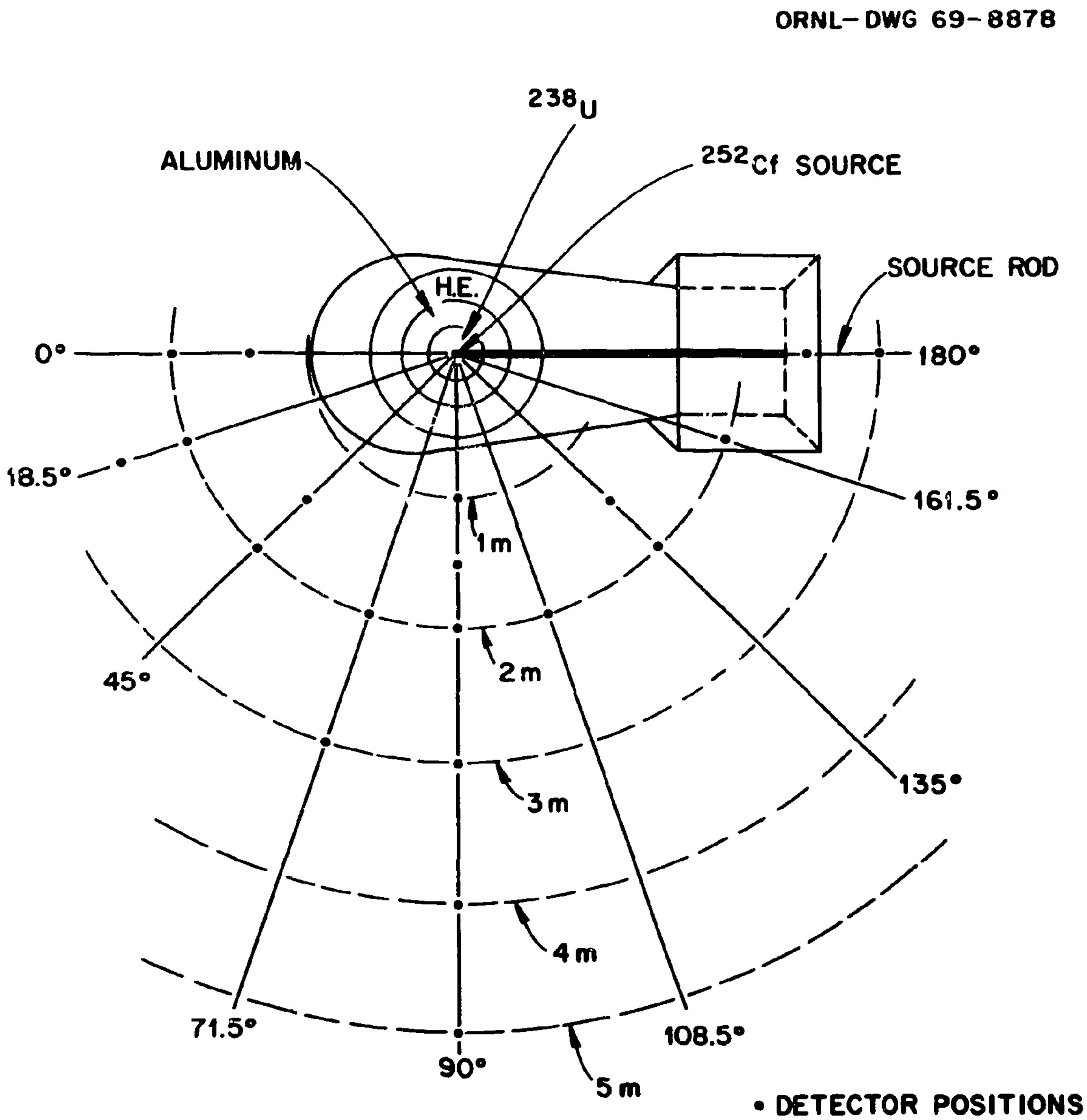


Fig. 9. Detector positions used in ORNL measurements of leakage radiation from Fat Man, looking down from above (Oak Ridge National Laboratory, 1969).

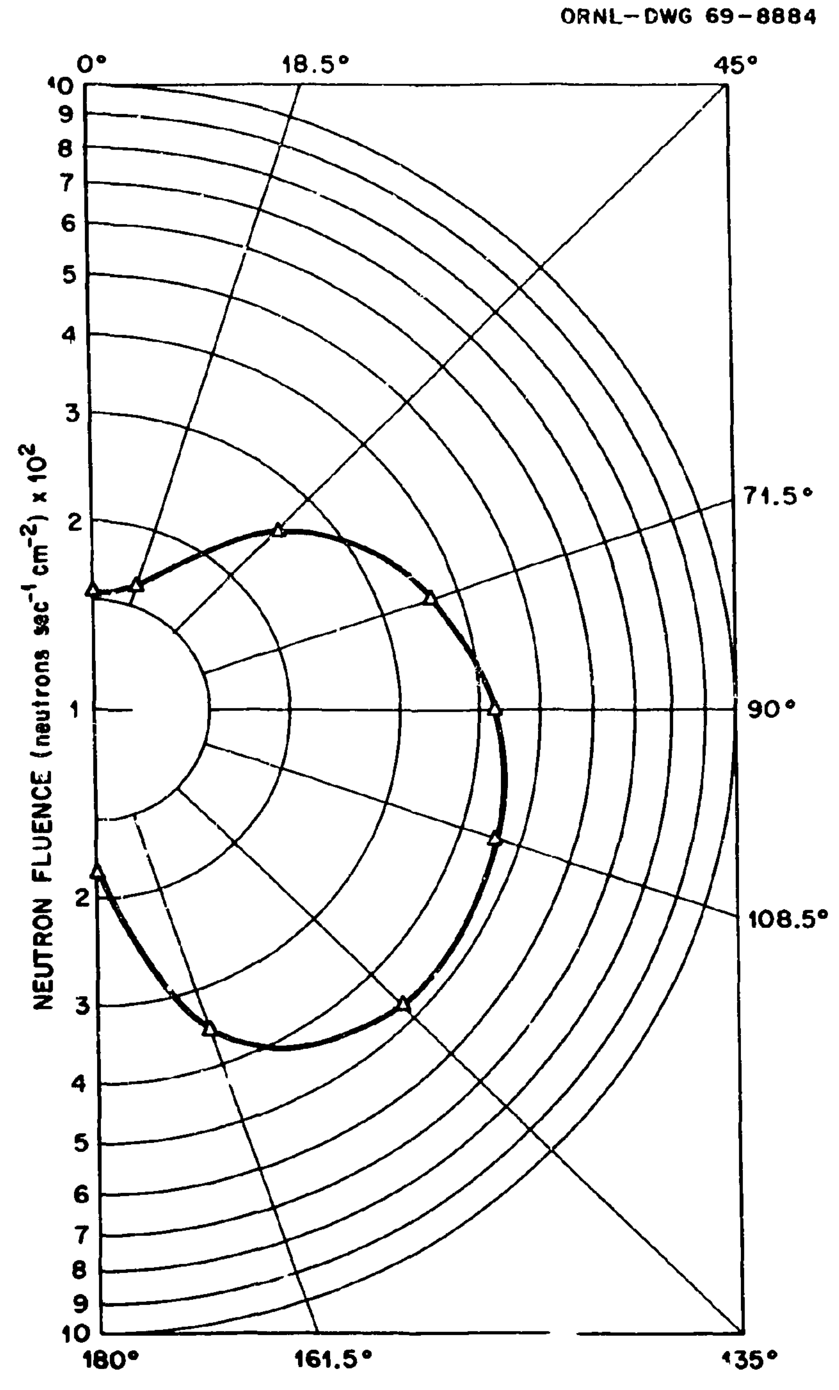


Fig. 10. Neutron flux measured at a radius of 2 m from a $^{252}Cf$ source at center of Little Boy's core. The neutron emission rate of the source was $6.07 \times 10^{8}$ n $s^{-1}$ (Wagner and Shinpaugh, 1968).

Table 6. Leakage of fast neutrons based on ORNL experiments using a duplicate Little Boy device (Oak Ridge National Laboratory, 1969)

| Angle of neutron flux measurement, θ (degrees) | Angular interval about flux measurement, θ (degrees) | Element of area represented by flux measurement,[a] ΔS ($cm^2$) | Measured neutron flux, Φ ($n\ cm^{-2}\ s^{-1}$) | Neutron leakage rate, ΦΔS ($n\ s^{-1}$) |
|---|---|---|---|---|
| 0 | 0 to 9.25 | 3.27 E+3[b] | 153 | 5.00 E+5 |
| 18.5 | 9.25 to 27.75 | 2.56 E+4 | 161 | 4.12 E+6 |
| 45.0 | 27.75 to 62.25 | 1.05 E+5 | 255 | 2.58 E+7 |
| 71.5 | 62.26 to 80.75 | 7.66 E+4 | 356 | 2.73 E+7 |
| 90.0 | 80.75 to 99.25 | 8.08 E+4 | 418 | 3.38 E+7 |
| 108.5 | 99.25 to 117.75 | 7.66 E+4 | 449 | 3.44 E+7 |
| 135.0 | 117.75 to 152.25 | 1.05 E+5 | 466 | 4.89 E+7 |
| 161.5 | 152.25 to 170.75 | 2.56 E+4 | 350 | 8.96 E+6 |
| 180.0 | 170.75 to 180.0 | 3.27 E+3 | 185 | 6.05 E+5 |
| Total | | 5.03 E+5 | | 1.85 E+8 |

Emission rate of neutrons from Californium-252 source = 6.07 E+8 $n\ s^{-1}$

$$\text{Leakage of source neutrons from the weapon} = \frac{\text{Neutron leakage rate}}{\text{Source emission rate}} = \frac{1.85\text{ E+8}}{6.07\text{ E+8}} = 0.30$$

[a]Neutron flux measured at a radius of 2 m from $^{252}Cf$ fission-neutron source located at center of weapon.

[b]Read as $3.27 \times 10^3$, etc.

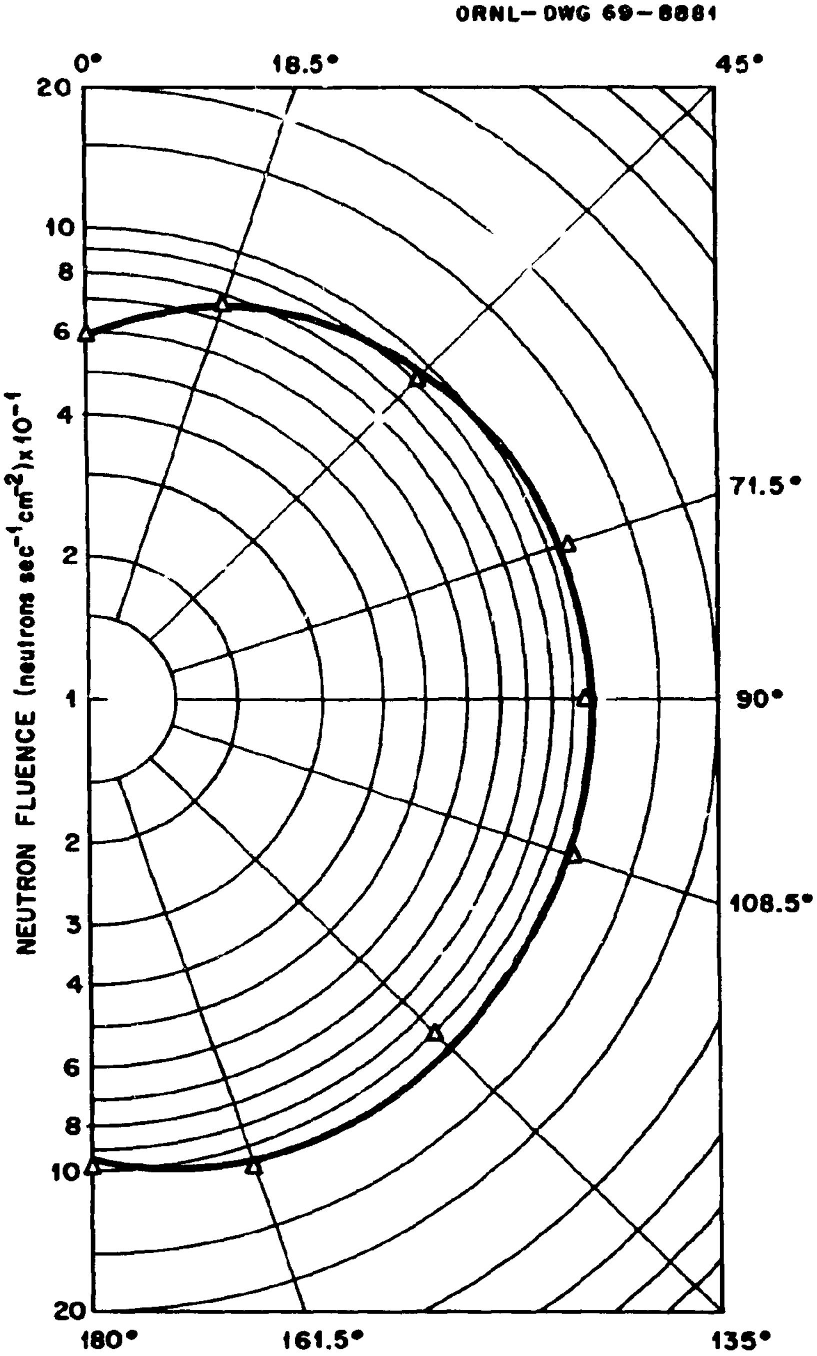


Fig. 11. Neutron flux measured at a radius of 2 m from a $^{252}Cf$ source at center of Fat Man's core. The neutron emission rate of the source was 6.07 x $10^8$ n $s^{-1}$ (Wagner and Shinpaugh, 1968).

The experimental ORNL data and the theoretical LANL data on neutron leakage from Fat Man differ significantly (see Table 5). Because of the high hydrogen content of the thick HE layer about Fat Man's core, most of the fast neutrons were moderated down to thermal energies before they escaped from the device. The thermalized neutrons from the "cold" device used in the ORNL measurements had energies of approximately 0.025 eV, while the thermalized "bomb" neutrons from the "hot" device considered in the LANL calculations have energies of the order of 0.1 keV. In fact, the high energy tail of the Maxwellian distribution (Murray, 1957) of thermalized "bomb" neutrons extended up into the fast neutron-energy region above 1 keV. Only a small percentage of the neutrons escaped from Fat Man as fast neutrons, but they were quite energetic because of "hardening" of the fast-neutron spectrum by the hydrogen (Ing and Cross, 1975a) in the thick HE layer. The leakage spectrum of fast neutrons (and "bomb" thermal neutrons with energies above 1 keV) had an average energy of about 1.6 MeV in the case of Fat Man and only about 0.3 MeV in the case of Little Boy. Mostly fast neutrons escaped from Little Boy, but they were severely degraded in energy because of "softening" of the fast-neutron spectrum by the iron (Ing and Cross, 1975b) in its massive steel casing.

The experimental ORNL data and the theoretical LANL data on both "hot" and "cold" devices seemed to indicate that the effect of weapon burnup on neutron leakage from Little Boy was small (see Table 5), and the T65D neutron-leakage factor of 1.00 x $10^7$ Gy $m^2$ $kton^{-1}$ was found to agree quite well with that obtained from Preeg's 1976 calculations of the neutron-leakage spectrum from Little Boy (see Table 7) (Kerr, 1979b). Thus, substantial agreement was found among the theoretical and experimental data related to neutron leakage from the Ichiban Critical Assembly and the Little Boy device, and the investigation failed to resolve the large discrepancy between the older T65D estimates (Auxier et al., 1966) and newer theoretical calculations (J. Pace, 1977) of the neutron exposure in Hiroshima. Air-ground interface effects (French and Mooney, 1970; Straker, 1971) were also eliminated as a source of this large discrepancy through a series of theoretical and experimental investiga-

Table 7. Neutron-leakage factor for tissue kerma from neutrons at the burst point of Little Boy based on neutron-leakage-spectrum calculations by Preeg (1976)

| Energy interval (MeV) | Energy spectrum of leakage neutrons, ΔN (n kton$^{-1}$) | Normalized energy spectrum of leakage neutrons, ΔN* = ΔN/N | Tissue kerma per fluence neutron,[a] K (Gy n$^{-1}$ cm$^2$) | Mean tissue kerma per fluence neutron, KΔN* (Gy n$^{-1}$ cm$^2$) |
|---|---|---|---|---|
| 6.07 E+0 to 7.79 E+0[b] | 9.54 E+19 | 7.68 E-4 | 4.95 E-11 | 3.80 E-14 |
| 3.68 E+0 to 6.07 E+0 | 3.65 E+20 | 2.94 E-3 | 4.35 E-11 | 1.28 E-13 |
| 2.865 E+0 to 3.68 E+0 | 4.39 E+20 | 3.53 E-3 | 3.96 E-11 | 1.40 E-13 |
| 2.232 E+0 to 2.865 E+0 | 7.79 E+20 | 6.27 E-3 | 3.38 E-11 | 2.12 E-13 |
| 1.738 E+0 to 2.232 E+0 | 1.21 E+21 | 9.74 E-3 | 3.13 E-11 | 3.05 E-13 |
| 1.353 E+0 to 1.738 E+0 | 1.54 E+21 | 1.24 E-2 | 2.80 E-11 | 3.47 E-13 |
| 8.23 E-1 to 1.353 E+0 | 5.18 E+21 | 4.17 E-2 | 2.42 E-11 | 1.01 E-12 |
| 5.00 E-1 to 8.23 E-1 | 1.19 E+22 | 9.58 E-2 | 1.82 E-11 | 1.74 E-12 |
| 3.03 E-1 to 5.00 E-1 | 1.85 E+22 | 1.49 E-1 | 1.51 E-11 | 2.25 E-12 |
| 1.84 E-1 to 3.03 E-1 | 1.65 E+22 | 1.33 E-1 | 1.19 E-11 | 1.58 E-12 |
| 6.76 E-2 to 1.84 E-1 | 2.77 E+22 | 2.23 E-1 | 7.94 E-12 | 1.77 E-12 |
| 2.48 E-2 to 6.76 E-2 | 1.18 E+22 | 9.50 E-2 | 5.00 E-12 | 4.75 E-13 |
| 9.12 E-3 to 2.48 E-2 | 1.81 E+22 | 1.46 E-1 | 1.59 E-12 | 2.32 E-13 |
| 3.35 E-3 to 9.12 E-3 | 3.98 E+21 | 3.21 E-2 | 6.18 E-13 | 1.98 E-14 |
| 1.235 E-3 to 3.35 E-3 | 3.21 E+21 | 2.58 E-2 | 2.37 E-13 | 6.13 E-15 |
| 4.54 E-4 to 1.235 E-3 | 2.11 E+21 | 1.70 E-2 | 8.57 E-14 | 1.46 E-15 |
| 1.67 E-4 to 4.54 E-4 | 5.74 E+20 | 4.62 E-3 | 3.50 E-14 | 1.62 E-16 |

Table 7 (continued)

| Energy interval (MeV) | Energy spectrum of leakage neutrons, $\Delta N$ (n $kton^{-1}$) | Normalized energy spectrum of leakage neutrons, $\Delta N^* = \Delta N/N$ | Tissue kerma per fluence neutron,[a] K (Gy $n^{-1}$ $cm^2$) | Mean tissue kerma per fluence neutron, $K\Delta N^*$ (Gy $n^{-1}$ $cm^2$) |
|---|---|---|---|---|
| 6.14 E-5 to 1.67 E-4 | 1.69 E+20 | 1.36 E-3 | 1.51 E-14 | 2.05 E-17 |
| 2.26 E-5 to 6.14 E-5 | 3.76 E+19 | 3.03 E-4 | 1.05 E-14 | 3.18 E-18 |
| Total | 1.24 E+23 | 1.00 E+0 | | 1.03 E-11 |

Neutron-leakage factor = $(1/4\pi)$(1.24 E+23 n $kton^{-1}$)(1.03 E-11 Gy $n^{-1}$ $cm^2$)(1 m/100 cm)$^2$

= 1.02 E+7 Gy $m^2$ $kton^{-1}$

[a]See Appendix B, National Council on Radiation Protection (1971a).

[b]Read as 6.07 x $10^0$ or 6.07, etc.

tions in 1979-1980 using the U.S. Army Pulsed Radiation Division Reactor (APRDR) (Kazi et al., 1979; Robitaille and Hoffarth, 1980).

## SULFUR ACTIVATION DATA

Several other investigations of this review aimed at resolving the discrepancy between the newer theoretical calculations (J. Pace, 1977) and T65D estimates (Auxier et al., 1966) of neutron exposure in Hiroshima gave ambiguous results. This was especially true of sulfur activation by fast neutrons which was more easily related to neutron leakage from the weapons than thermal neutron activation of phosphorus in bone samples, trace elements in the ground, and cobalt in steel samples (Wilson, 1956; N. Pace and Smith, 1959; Arakawa, 1962; Takeshita, 1975; Hashizume and Maruyama, 1975b). The neutron-leakage calculations by Preeg (1976) and the neutron-transport calculations by J. Pace (1977) for the Fat Man device exploded in Nagasaki were substantiated in 1980 by Kerr (see Fig. 12) using data on fluence of fast neutrons with energies above 2.5 MeV as indicated by sulfur activation measurements made during the Trinity test (N. Pace and Smith, 1959; Klema, 1945) and the Crossroads Able test (Biggers and Waddell, 1957; Glasstone, 1950). However, the newer theoretical calculations by Preeg (1976) and J. Pace (1977) predicted a relative value (Hiroshima/Nagasaki) for sulfur activation of about unity compared with about three, quoted by Wilson (1956), and about 3.5, which is obtained if the sulfur activation is assumed to be proportional to the T65D estimates of tissue kerma from neutrons at ground zero in the two cities (Kerr, 1980a).

A major breakthrough in the review came in July 1980 from a report by Miyazaki and Masuda (1953) on Japanese radiation surveys made immediately after the bombings in 1945. This paper states: "The intensity of radiation (from neutron activation of the ground) about the hypocenter (or ground zero) is approximately 45 J (where 1 J is equivalent to one ion-pair $s^{-1}$ $cm^{-3}$ of air under standard conditions or a tissue kerma rate of about 17.5 pGy $hr^{-1}$) both in Nagasaki and Hiroshima (about six months after the bombings). According to K. Kimura the intensity of

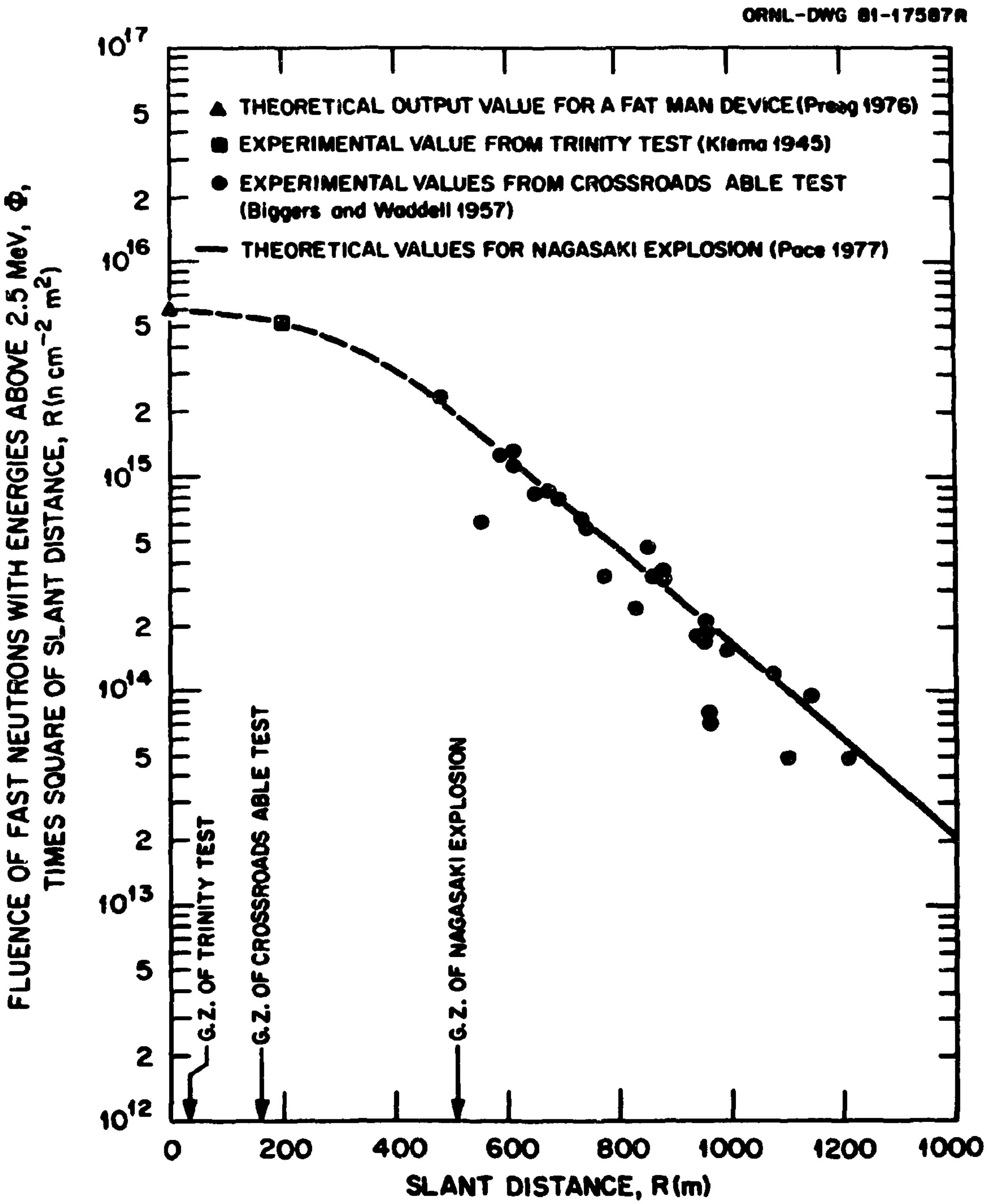


Fig. 12. Comparison of the theoretical and experimental data on the fluence of fast neutrons with energies above 2.5 MeV as a function of ln ($\Phi R^2$) vs R, where $\Phi$ is the neutron fluence and R is the slant distance from the burst point of the weapon.

radiophosphorus caused by slow (or thermal) neutrons in Hiroshima was four times that in Nagasaki, while the intensity of radioactive sulfur caused by fast neutrons at Nagasaki was 1.6 times higher than at Hiroshima. Therefore, the cause of the intensity of radiation about the hypocenters has not been explained yet." The relative value (Hiroshima/ Nagasaki) of 0.63 for sulfur activation in this report is quite different from the relative value of about three quoted by Wilson (1956). An extensive investigation was, therefore, undertaken of data related to sulfur activation from the two weapons (Kerr, 1980a; 1980b).

The most detailed and widely referenced set of data on measurements of radioactive $^{32}P$ produced by the reaction $^{32}S(n,p)^{32}P$ in sulfur used in insulators of utility poles in Hiroshima appears in reports by Yamasaki and Sugimoto (1945; 1953b) and by N. Pace and Smith (1946; 1959). All these reports contain data (see Table 8) on disintegrations per minute (dpm) per gram of sulfur (gm of S) extrapolated to August 6, 1945, from measurements made on September 20, 1945. These measurements of the beta particles from the decay of $^{32}P$ were made through an 0.0015-mm aluminum window of a calibrated Lauritsen electrometer at the Institute of Physical and Chemical Research in Tokyo, which had been heavily involved in Japanese research on atomic weapons during the war (Pacific War Research Society, 1972; Coffey, 1971). The most accessible of the above reports is the one published in 1946 by N. Pace and Smith which was reprinted in 1959 by the ABCC.

No equivalent data from measurements using a calibrated detector could be found for sulfur activation in Nagasaki. The report by Nakaidzumi (1945) which was referenced by Wilson (1956) gives no information on sulfur activation in either city; it only provides estimates of the fast-neutron fluence in Hiroshima derived from the sulfur activation study of Yamasaki and Sugimoto in late 1945, when the cross section of the $^{32}S(n,p)^{32}P$ reaction was not well known (Yamasaki and Sugimoto, 1953b; Japanese Army Medical School, 1953). If the estimated fast-neutron fluences in Hiroshima from Nakidzumi (1945) are compared with the estimates in Fig. 2 of Wilson (1956) for the fluence of fast neutrons with energies above 2.5 MeV in Nagasaki (or 3.0 MeV quoted by Wilson),

Table 8. Neutron-induced $^{32}P$ radioactivity in sulfur of utility pole insulators in Hiroshima from measurements by Yamasaki and Sugimoto (1945; 1953b)

| Sample[a] | Ground distance (m)[a,b] | Initial radioactivity (dpm per gm of S)[a,b,c] |
|---|---|---|
| A | 270 | 2200 |
| B | 120 | 2900 |
| C | 350 | 900 |
| D | 380 | 1100 |
| E | 100 | 2200 |
| F | 460 | 1100 |
| G | 440 | 1300 |
| H | 740 | 660 |
| J | 1000 | 210 |
| K | 860 | 340 |

[a]See map in Yamasaki, Sugimoto, and Kimura (1953a) and table in Yamasaki and Sugimoto (1953b).

[b]See Fig. 7 in N. Pace and Smith (1959).

[c]Radioactivity in disintegrations per minute (dpm) per gram of sulfur (gm of S) extrapolated to August 6, 1945, from measurements made on September 20, 1945.

then the relative values at ground distances between 0 and 500 m (see Table 9) indicate about three times as many neutrons above 2.5 MeV in Hiroshima as in Nagasaki.

Some better founded relative values for sulfur activation in the two cities were eventually derived from empirical equations fitted to the measurements of Yamasaki and Sugimoto (N. Pace and Smith, 1959) and the Crossroads Able measurements (Glasstone, 1950) (see Table 10). These empirical equations gave relative values (Hiroshima/Nagasaki) more consistent with the relative value of 0.63 quoted by Miyazaki and Masuda (1953) and the relative value of about unity derived from the theoretical neutron-leakage data of Preeg (1976) and theoretical neutron-transport data of J. Pace (1977). The initial sulfur activation was estimated from the reported fast-neutron fluences for the Crossroads Able test (Glasstone, 1950; Biggers and Waddell, 1957) using a cross section of 230 millibarns (or $0.23 \times 10^{-24}$ $cm^2$) with a probable error of about 30 millibarns (or ±15%) (Hurst and Ritchie, 1959; Allen et al., 1957; Bainbridge, 1947). In early measurements using sulfur as a threshold detector, the usual practice was to calibrate the counting system by irradiating a sulfur sample with a known fluence of 14-MeV neutrons and to report the activation of other samples in terms of the fluence of 14-MeV neutrons producing equal activation in the sulfur detectors. The value of 230 millibarns (±15%) agrees quite well with the cross section of about 255 millibarns for the $^{32}S(n,p)^{32}P$ reaction at 14 MeV (Allen et al., 1957) and the fission-spectrum weighted value of 229 millibarns used for the $^{32}S(n,p)^{32}P$ reaction in ORNL threshold-detector measurements made during later weapon tests (Hurst and Ritchie, 1958).

Finally, the results of a theoretical investigation of sulfur activation in the two cities, which takes into account the variation in the cross section of the $^{32}S(n,p)^{32}P$ reaction with neutron energy through the use of theoretical neutron-spectrum data from J. Pace's 1977 calculations, are shown in Figs. 13 and 14. Note that the theoretical values in Fig. 13 for sulfur activation in Nagasaki are in excellent agreement with the experimental data on the duplicate Fat Man device fired during the Crossroads Able test (Biggers and Waddell, 1957). The

Table 9. Estimates of the fluence of fast neutrons with energies greater than 2.5 MeV in Hiroshima from Nakaidzumi (1945) and in Nagasaki from Wilson (1956)

| Ground distance, (m) | Fluence of neutrons with energies greater than 2.5 MeV ($n\ cm^{-2}$) | | Hiroshima to Nagasaki ratio |
|---|---|---|---|
| | Hiroshima[a] | Nagasaki[b] | |
| 0 | $8.2 \times 10^{11}$ | $4.0 \times 10^{11}$ | 2.1 |
| 500 | $3.3 \times 10^{11}$ | $7.0 \times 10^{10}$ | 4.7 |
| 1000 | $7.0 \times 10^{10}$ | $6.5 \times 10^{9}$ | 10.8 |

[a]See fast neutron fluences in Table 66, map in Fig. 17-2, and sulfur activation data in Fig. 19 of report by Japanese Army Medical School (1953). These estimates of the fast neutron fluence in Hiroshima were derived from the sulfur activation measurements of Yamasaki and Sugimoto (1953b).

[b]See Fig. 2 in Wilson (1956). The effective threshold energy for the production of $^{32}P$ in sulfur by the reaction $^{32}S(n,p)\,^{32}P$ is quoted as 3.0 MeV instead of the 2.5 MeV used in this report.

Table 10. Estimates of sulfur activation by fast neutrons having energies greater than 2.5 MeV in Hiroshima from Yamasaki and Sugimoto (1953b) and in Nagasaki from Glasstone (1950)

| Ground distance (m) | Initial radioactivity of $^{32}P$ in sulfur (dpm per gm of S) | | Hiroshima to Nagasaki ratio |
|---|---|---|---|
| | Hiroshima[a] | Nagasaki[b] | |
| 0 | $2.8 \times 10^3$ | $9.5 \times 10^3$ | 0.29 |
| 500 | $1.0 \times 10^3$ | $1.6 \times 10^3$ | 0.63 |
| 1000 | $1.7 \times 10^2$ | $7.6 \times 10^1$ | 2.2 |

[a]See Fig. 7 of N. Pace and Smith (1959). These estimates are based on an empirical equation developed by them to describe the sulfur activation measurements by Yamasaki and Sugimoto (1953b).

[b]See Equation 7.58.1, Table 7.59, and Fig. 7.59 of Glasstone (1950). These estimates of the fast neutron fluence are based on sulfur activation measurements made during the Crossroads Able test. The effective threshold energy for the production of $^{32}P$ in sulfur by the reaction $^{32}S(n,p)\,^{32}P$ is quoted as 3.0 MeV instead of the 2.5 MeV used in this report. A mean cross section of 230 millibarn with a probable error of about 30 millibarns (±15%) was used in estimating the initial radioactivity of $^{32}P$ in sulfur from the fast-neutron fluences reported in Glasstone (1950).

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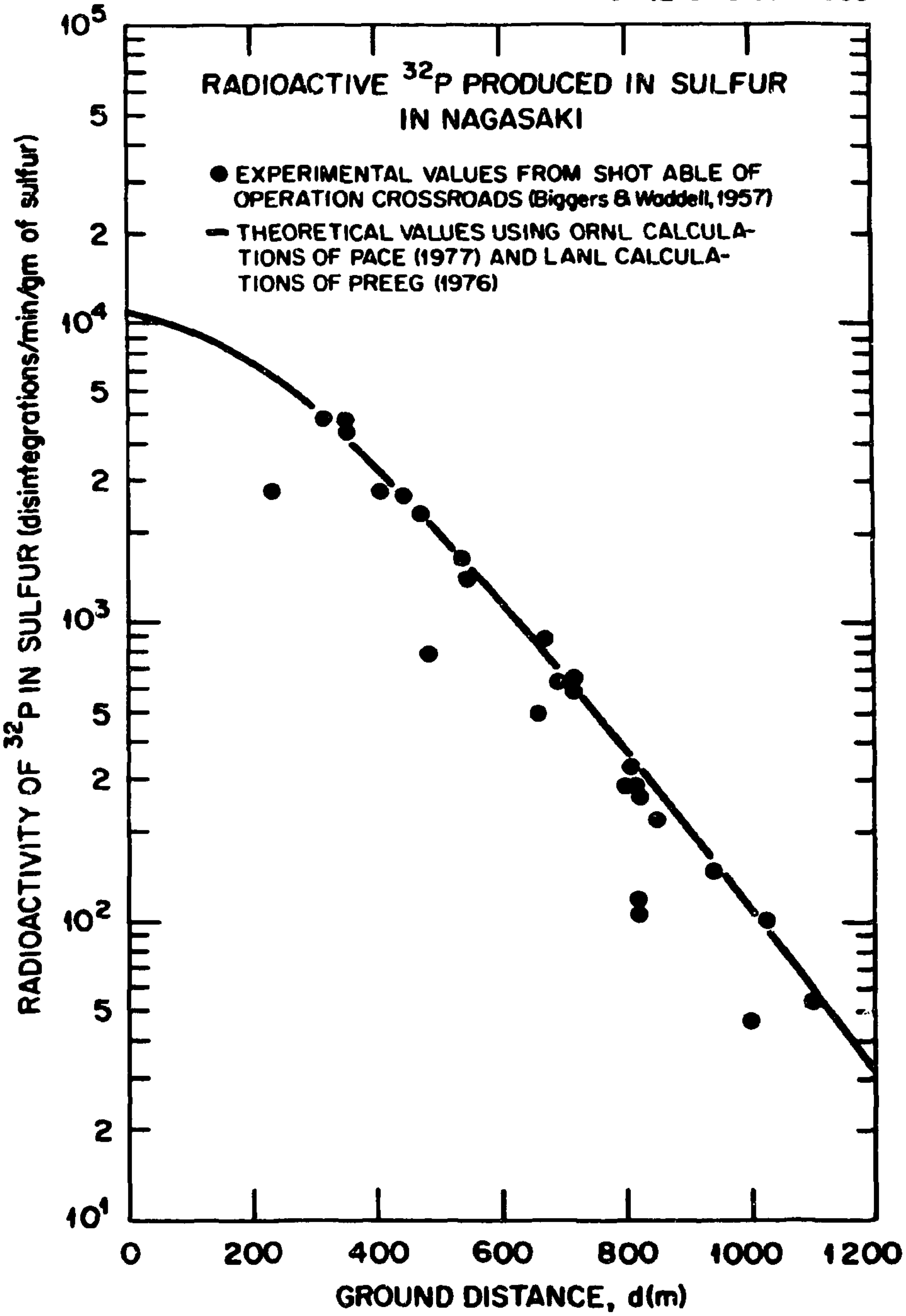


Fig. 13. Comparison of theoretical data on sulfur activation by the Fat Man device exploded in Nagasaki and experimental data on sulfur activation by the Fat Man device fired during the Crossroads Able test.

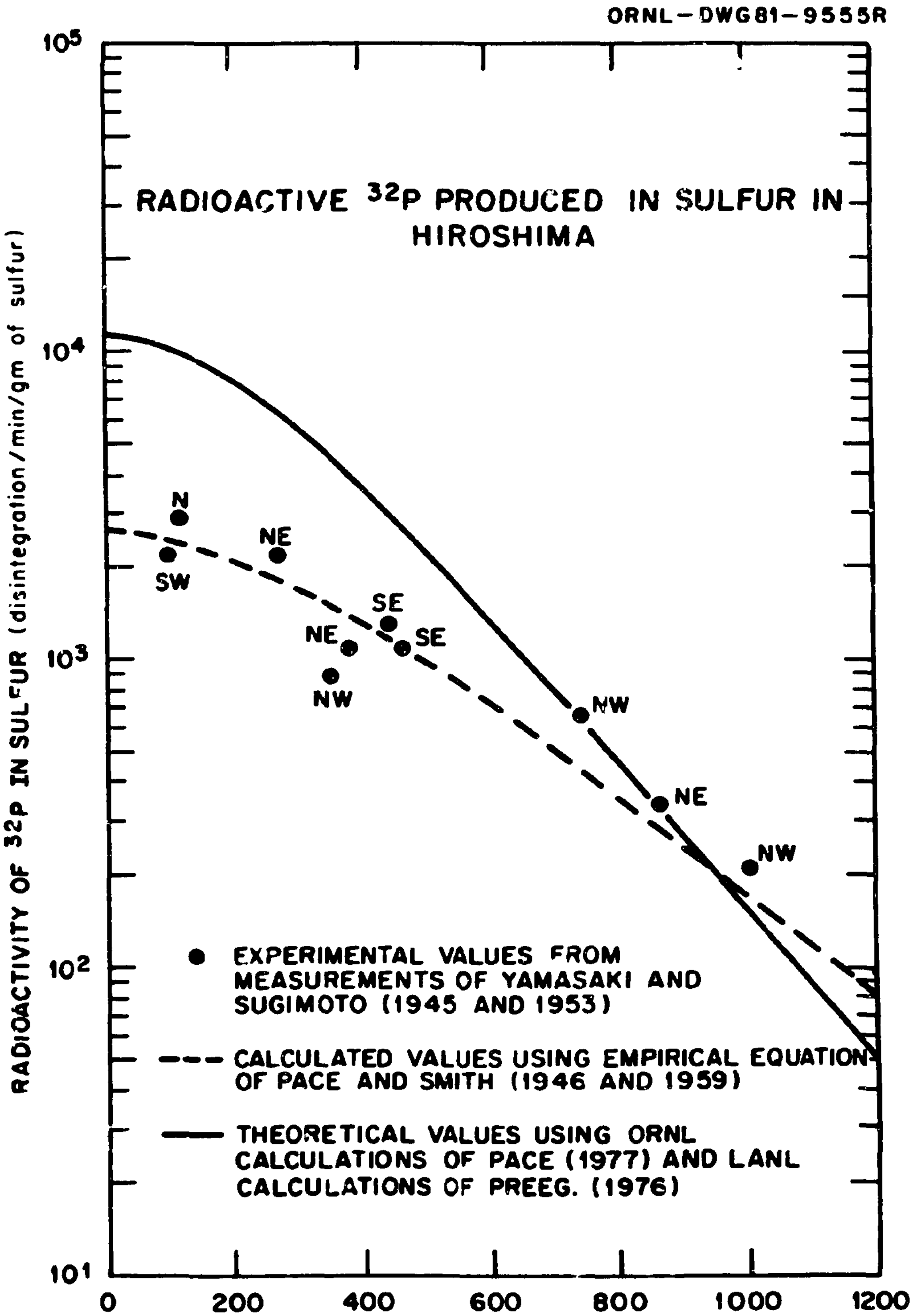


Fig. 14. Comparison of theoretical and experimental data on sulfur activation by the Little Boy device exploded in Hiroshima.

low Crossroads Able values probably resulted from inadvertent shielding of some sulfur detectors due to a rather large difference between the targeted and the actual burst point of the air-dropped device. A relative value (Hiroshima/Nagasaki) of about unity for sulfur activation near ground zero is predicted by the theoretical calculations (see Figs. 13 and 14). Note, however, that the theoretical data overestimate the sulfur activation according to the experimental data from measurements made near ground zero in Hiroshima, but at larger ground distances the experimental and theoretical data are in good agreement. It was eventually determined that this was probably due to the spherically symmetric mockup of Little Boy used by Preeg and to his calculated 1-D leakage from the device (Kerr, 1980b). The 1-D neutron-leakage approximation becomes less important at the larger ground distances of most interest (i.e., 1000 m or more) since neutron scattering in air will tend to mask any initial anisotropy in the actual neutron leakage from the cylindrically symmetric Little Boy device.

A blind spot in the neutron leakage through the nose of Little Boy was noted in the experimental measurements using a duplicate device (see 0 and 18.5° angles in Fig. 10). There was considerably more steel in the nose than in the sides of the device (Birch, 1947; Malik, 1981), and the differences in the leakage spectra of fast neutrons with energies above 2.5 MeV through the sides and nose (Bartine, 1981) were extremely important with regard to sulfur activation near ground zero in Hiroshima. A directional dependence was also noted in the experimental data on sulfur activation at ground distances of 500 m or less (see Fig. 14). The sulfur activation was lower, in general, to the west than to the east. This would have occurred if the weapon's nose were not pointed directly downward ATE. A calculation using drop data from a report by Caudle (1965) indicated that the weapon was canted ATE about 15° with respect to the vertical (Kerr, 1980b). Since the direction of approach of the bombing and observation aircraft was from ENE toward WSW (see Fig. 15) (United States Strategic Bombing Survey, 1947; Knebel and Bailey, 1960; Marx, 1967), the weapon's nose would have been pointed at a ground location about 150 m WSW of ground zero. The Fat Man device dropped in

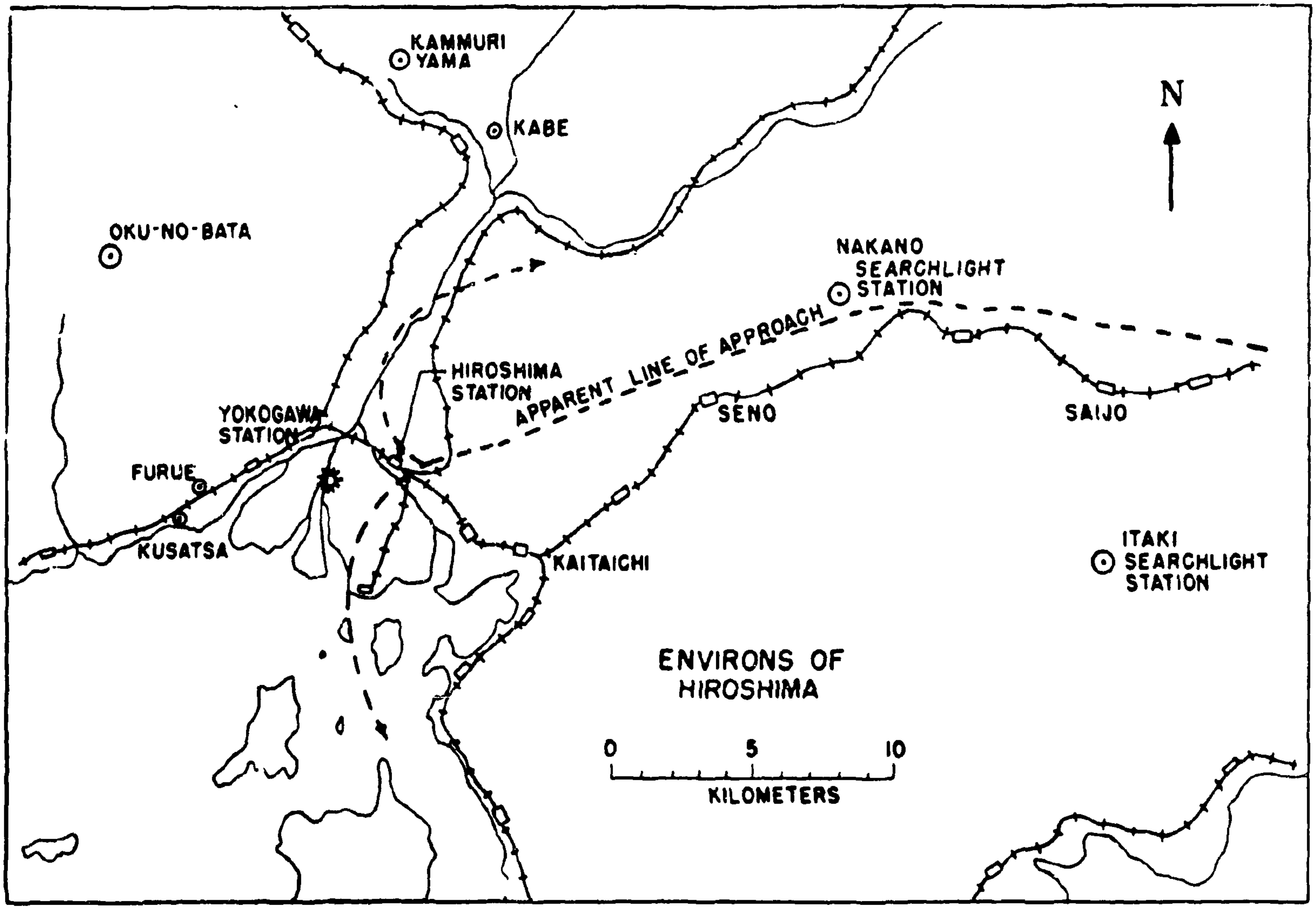


Fig. 15. Map showing environs of Hiroshima and direction of approach of the bombing and observation aircraft (United States Strategic Bombing Survey, 1947). The bombing aircraft turned to the north after releasing Little Boy, and the observation aircraft turned to the south after releasing three parachute-retarded canisters to record the air pressure of the explosion.

Nagasaki (Marx, 1971) was also probably cante [illegible] c about 15° to the vertical, but it was a spherically symmetric device with nearly isotropic neutron leakage (see Fig. 11).

## STEEL ACTIVATION DATA

Two steel samples from a steel-reinforced concrete building were used in the JNIRS study by Hashizume et al. (1967). One was a surface steel sample, and one was part of a steel reinforcing rod embedded at a depth of 8 cm (or 3 inches) in an exterior wall facing ground zero. The thermal neutron-induced $^{60}Co$ radioactivity was measured in the two samples, and the results were used to obtain a value for the $^{60}Co$ radioactivity in the 8-cm deep sample due to thermalization of fast neutrons within the concrete wall. To convert this value to a tissue kerma from fast neutrons, Hashizume et al. (1967) used the HPRR neutron-leakage spectrum, which provides a mean tissue kerma of about $2.5 \times 10^{-11}$ Gy per unit fluence (n $cm^{-2}$) of fast neutrons having energies greater than 1 keV. Since the theoretical neutron-transport calculations by J. Pace (1977) gave a much smaller value, about $1.0 \times 10^{-11}$, for this kerma in Hiroshima, the JNIRS estimates of neutron exposure in Hiroshima were predicted to be high by a factor of at least two and one-half (Kerr, 1980a).

It was discovered before a more detailed investigation of the JNIRS steel-activation data was started at ORNL that these data were also being investigated at Lawrence Livermore National Laboratory (LLNL). At an ORNL meeting on August 20, 1980, Loewe and Mendelsohn (1980a) of LLNL discussed their studies related to the dosimetry for atomic-bomb survivors. They had attempted to use the LANL neutron-leakage data of Preeg (1976) to calculate the JNIRS measured $^{60}Co$-activation value at a ground distance of 1180 m in Hiroshima (Hashizume et al., 1967), but the agreement between the JNIRS measured value and the LLNL calculated value was very poor. The reason for the poor agreement was resolved as a result of the ORNL meeting (Loewe, 1980b), and the LLNL calculations eventually provided a revised JNIRS estimate of 0.11 Gy for the tissue kerma from neutrons at a ground distance of 1180 m in Hiroshima compared with the original JNIRS estimate of 0.51 Gy (Loewe and Mendelsohn, 1980a). Thus, it was concluded from the various investigations of data on neutron activation of sulfur and steel that there was significant bias in the T65D estimates of neutron exposure in Hiroshima.

## TISSUE KERMA FROM NEUTRONS

Calculations of the weapon radiation fields in air-over-ground at the large ground distances of interest (i.e., 1000 m or more) demanded the use of a computer code employing discrete ordinate transport (DOT) techniques and a relatively small set of coupled neutron and gamma-ray interaction cross sections (Abbott, 1973). One such set, developed at ORNL at the request of DNA for general use in modern nuclear weapon calculations, consists of 37 neutron and 21 gamma-ray groups (Bartine et al., 1977). It employs a 300°K Maxwellian weighting spectrum for the thermal neutron group and a 1/E weighting spectrum for all higher-energy neutron groups. This cross-section set was used by J. Pace in his 1977 calculations for Little Boy and Fat Man. The 1980 calculations by Loewe and Mendelsohn (1980a) of LLNL suggested that the above 37 neutron-group set of cross sections overestimated the neutron exposure in the case of the severely degraded-energy spectrum of fast neutrons from Little Boy.

Updated calculations by J. Pace (1981) of ORNL and Kaul (1981) of SAI using cross-section sets tailored more appropriately to Little Boy and Fat Man are shown in Figs. 16 and 17 (Kerr, 1981). Kaul also used a moist air composition typical of that existing in each of the two cities ATE (see Table 4) rather than the dry NTS-type air of his 1977 calculations. Note that there is only a small difference between the results of J. Pace's 1977 and 1981 calculations of the neutron exposure in Nagasaki from Fat Man, which had an extremely energetic leakage spectrum of fast neutrons compared with Little Boy. The results of the most recent calculations by LLNL (Loewe and Mendelsohn, 1980a), SAI (Kaul, 1981), and ORNL (J. Pace, 1981), which use somewhat different neutron cross-section data and neutron energy-group structures but the same DOT

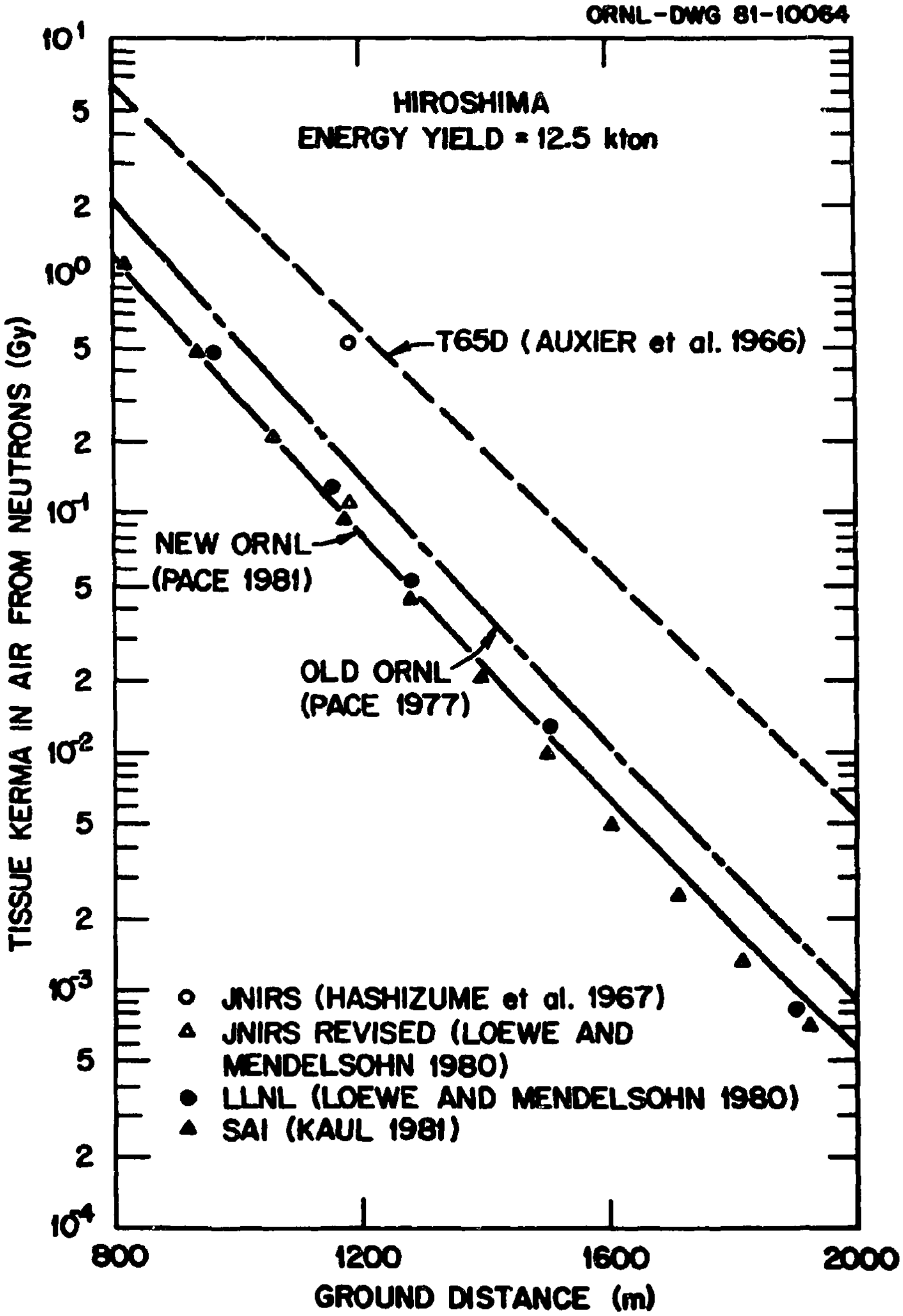


Fig. 16. Comparison of data on neutron exposure in Hiroshima as a function of ground distance.

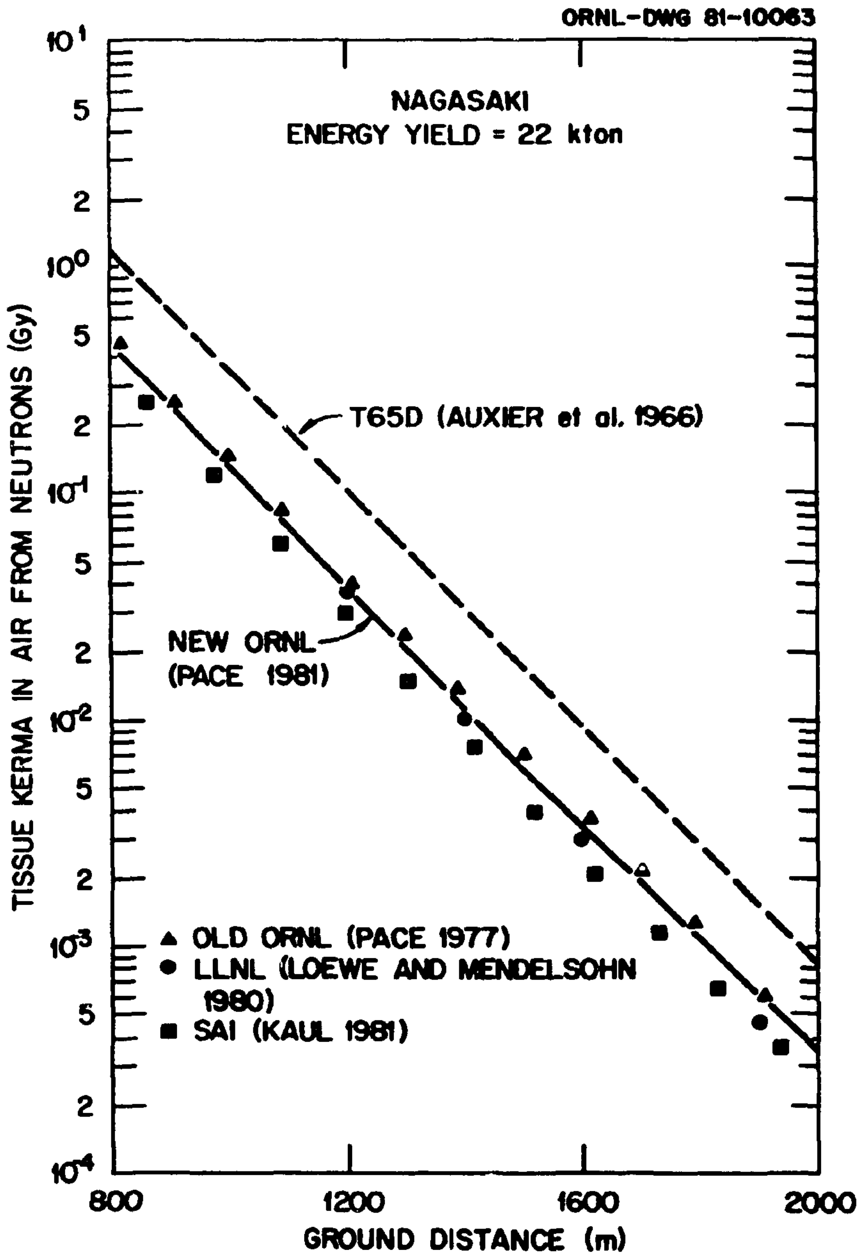


Fig. 17. Comparison of data on neutron exposure in Nagasaki as a function of ground distance.

calculation techniques, are now in close agreement with regard to the neutron exposure in Hiroshima.

The air-over-ground calculations by J. Pace (1981) used a four element ground (J. Pace et al., 1975) and a layered moist air having an exponentially decreasing density between the ground and the burst height of the weapon (see Table 4). Findings by J. Pace (1979) regarding the importance of moisture content in the atmosphere on neutron penetration are consistent in general with a study by Banks et al. (1978). In comparison with the effect of atmospheric moisture content on neutron (and secondary gamma-ray) penetration in air-over-ground, the studies by Banks et al. (1978) and Gritzner et al. (1976) indicate that composition and moisture content of ground are relatively unimportant. However, it would appear prudent to better characterize both the major and minor constituents of the ground in Hiroshima and Nagasaki (Arakawa, 1962; Hashizume et al., 1969; Hashizume and Maruyama, 1975b).

## TISSUE KERMA FROM GAMMA RAYS

The DOT calculations using Preeg's leakage data on both neutrons and gamma rays (see Tables 2 and 3) give the radiation exposure to neutrons and gamma rays from the exploding weapon and to secondary gamma rays produced by neutron interactions in the air and ground. To these radiation components must be added gamma rays emitted by the decay of fission products in the fireball formed after the explosion. Calculation of the latter is quite complex due to the immediate rise of the fireball, the rapid decay of fission products in it, and the blast-wave enhancement of the radiation exposure to these gamma rays. The radiation exposures to delayed neutrons from the fireball and secondary gamma rays produced by delayed neutrons are thought to be negligibly small, but these components need to be investigated further.

An important parameter which is not taken into account in treatments of the fireball gamma-ray field of a weapon such as those in the 1977 Edition of *The Effects of Nuclear Weapons* (ENW-77) (Glasstone and Dolan, 1977) and *DNA Effects Manual No. 1* (EM-1) (Defense Nuclear

Agency, 1972) is the relative source strength of the gamma rays from the fission products of the various fissionable isotopes of uranium and plutonium. Marcum of R & D Associates (RDA) pointed out in a 1978 review of data related to dosimetry for atomic-bomb survivors that gamma rays from the fission products of $^{235}U$, $^{239}Pu$, and $^{238}U$ have relative source strengths of about 1.00, 0.67, and 1.75, respectively (Marcum, 1978). Little Boy was nearly all $^{235}U$, whereas Fat Man, according to both Preeg and Marcum, had about 80% of its fissions in the $^{239}Pu$ core and 20% in the $^{238}U$ tamper. If $^{235}U$ is used as a standard, then Fat Man would have a relative source strength of about 0.88 (Marcum, 1978). These source values are reflected in an important way in the total gamma-ray exposure since the fireball gamma-ray component is comparable in magnitude with that from secondary gamma rays.

A study to improve the modeling of the fireball gamma-ray field of a nuclear weapon was undertaken in 1980 by Scott of SAI, and he concluded that comparisons with the best available weapon test measurements were improved when the correct time-dependent decay spectra of gamma rays from the fission products of uranium and plutonium were included in the calculations (Scott, 1981). The agreement between measured and calculated values was within 10 to 20% when the appropriate isotopic time-dependent sources for a tested weapon were incorporated in the NUIDEA code of SAI (Straker and Husar, 1976) which uses the so-called LAMB blast-wave enhancement and fireball-rise models (Needham and Whittmer, 1975). One important finding of Scott's 1980 study was that the data in EM-1 and ENW-77 overestimate the radiation exposure from the fireball gamma-ray field of Little Boy and Fat Man by factors of two or more.

The results of the best state-of-the-art calculations by Scott (1981) and J. Pace (1981) have been summed to obtain the gamma-ray exposure values for Hiroshima and Nagasaki shown in Figs. 18 and 19 (Kerr, 1981). Energy yields and burst heights of 22 kton and 503 m were used for the Nagasaki explosion, and 12.5 kton and 580 m for the Hiroshima explosion. Note that the calculated values and experimental JNIRS values, which for reasons discussed earlier are usually considered to be the more reliable of the two Japanese data sets, agree to within 10% in

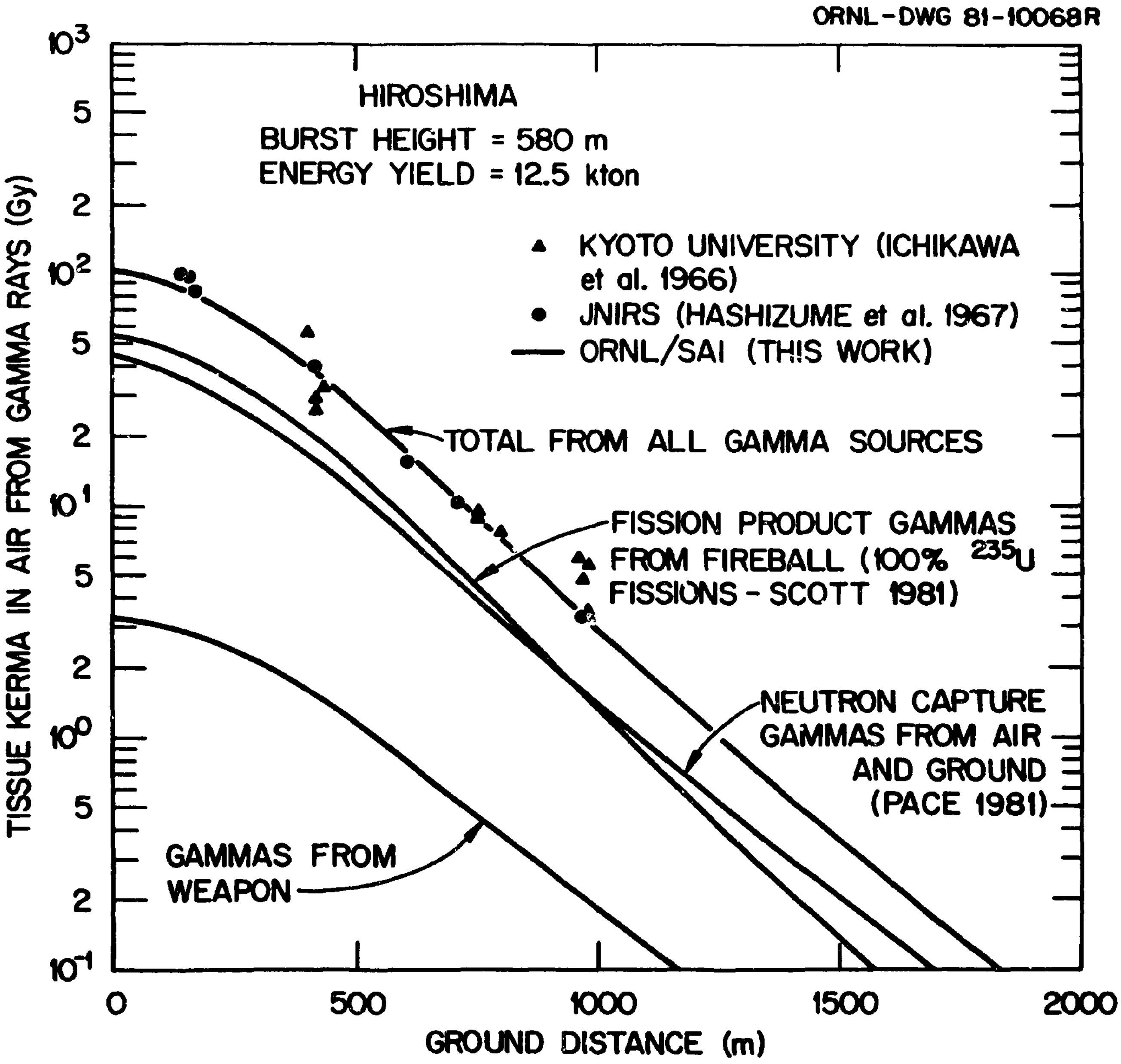


Fig. 18. Comparison of theoretical and experimental data on gamma-ray exposure in Hiroshima as a function of ground distance.

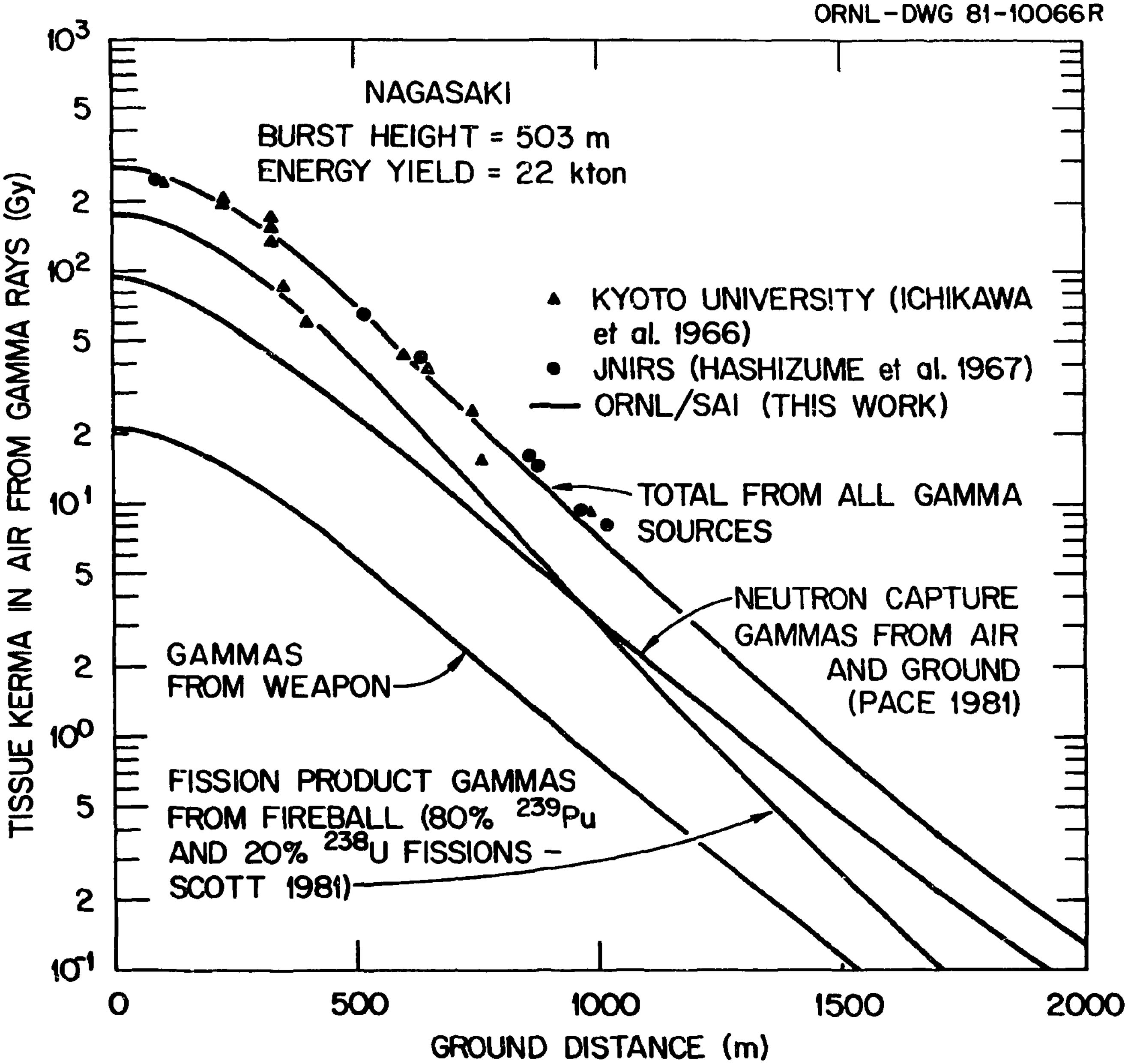


Fig. 19. Comparison of theoretical and experimental data on gamma-ray exposure in Nagasaki as a function of ground distance.

Hiroshima. The overall agreement is not as good in Nagasaki, where the difference is about 20% at a ground distance of about 1000 m. Sensitivity studies, which are needed to set limits of precision on the calculated values for both neutrons and gamma rays, may help to resolve the reasons for the larger observed difference in Nagasaki.

## KERMA RELAXATION LENGTH

Values of the radiation exposure from the recent calculations by J. Pace (1981) and Scott (1981) are compared with those from the T65D tissue kerma vs distance relationships of Auxier et al. (1966) in Figs. 20 and 21, as functions of ln $(KR^2)$ and R, where K is the tissue kerma in air and R is the slant distance from the burst point of the weapon (see Fig. 4). If the plot of ln $(KR^2)$ vs R is a straight line, then the radiation exposure can be specified by the relationship

$$K = G_o \frac{\exp(-R/L)}{R^2} \tag{2}$$

where $G_o$ is the extrapolated source term (i.e., ordinate intercept) and L is the kerma relaxation length (i.e., slope of the straight line). This equation was assumed in the T65D study (Auxier et al., 1966) and several previous studies of dosimetry for the Japanese atomic-bomb survivors (York, 1957; Wilson, 1956; Harris, 1955b) (see Table 11).

The calculations by J. Pace (1981) yielded essentially the same kerma relaxation length for neutrons in Nagasaki as that assumed in the T65D study for neutrons in both cities (see Fig. 20). During the Operation BREN studies with the HPRR (Stephens and Aceto, 1962) and a variety of modern weapon tests (Auxier et al., 1961; Hurst and Ritchie, 1958; Harris et al., 1955a), an invariant or equilibrium spectrum of air transport neutrons was observed starting at a distance R of several hundred meters, and the kerma relaxation length for neutrons was found to be a constant at greater distances (Glasstone 1957; 1962). This simply did not happen in Hiroshima due to the severely degraded energy

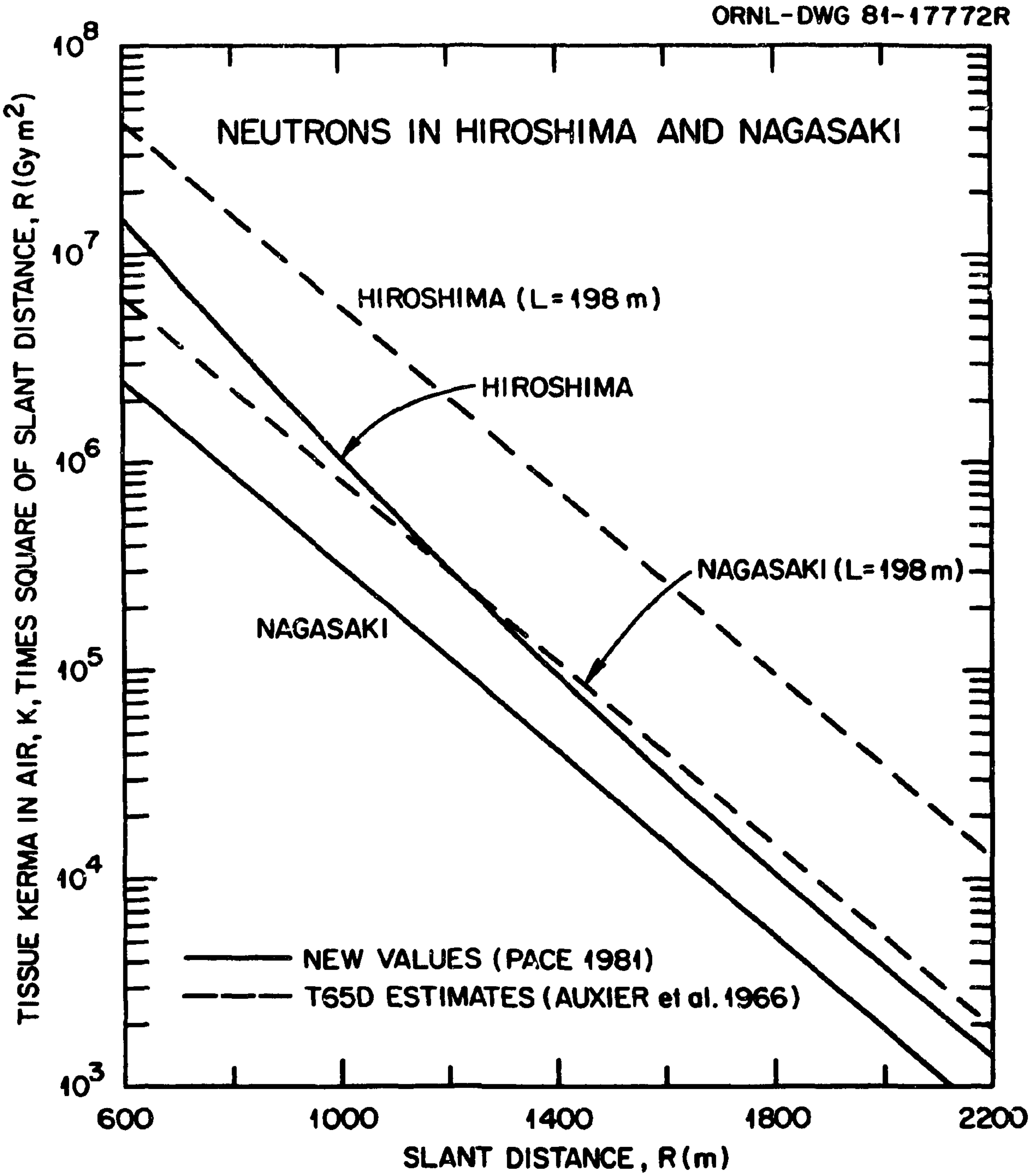


Fig. 20. Comparison of best state-of-the-art calculations and T65D estimates of the neutron exposure in Hiroshima and Nagasaki as a function of ln $(KR^2)$ vs R, where K is tissue kerma in air and R is the slant distance from the burst point of the weapon.

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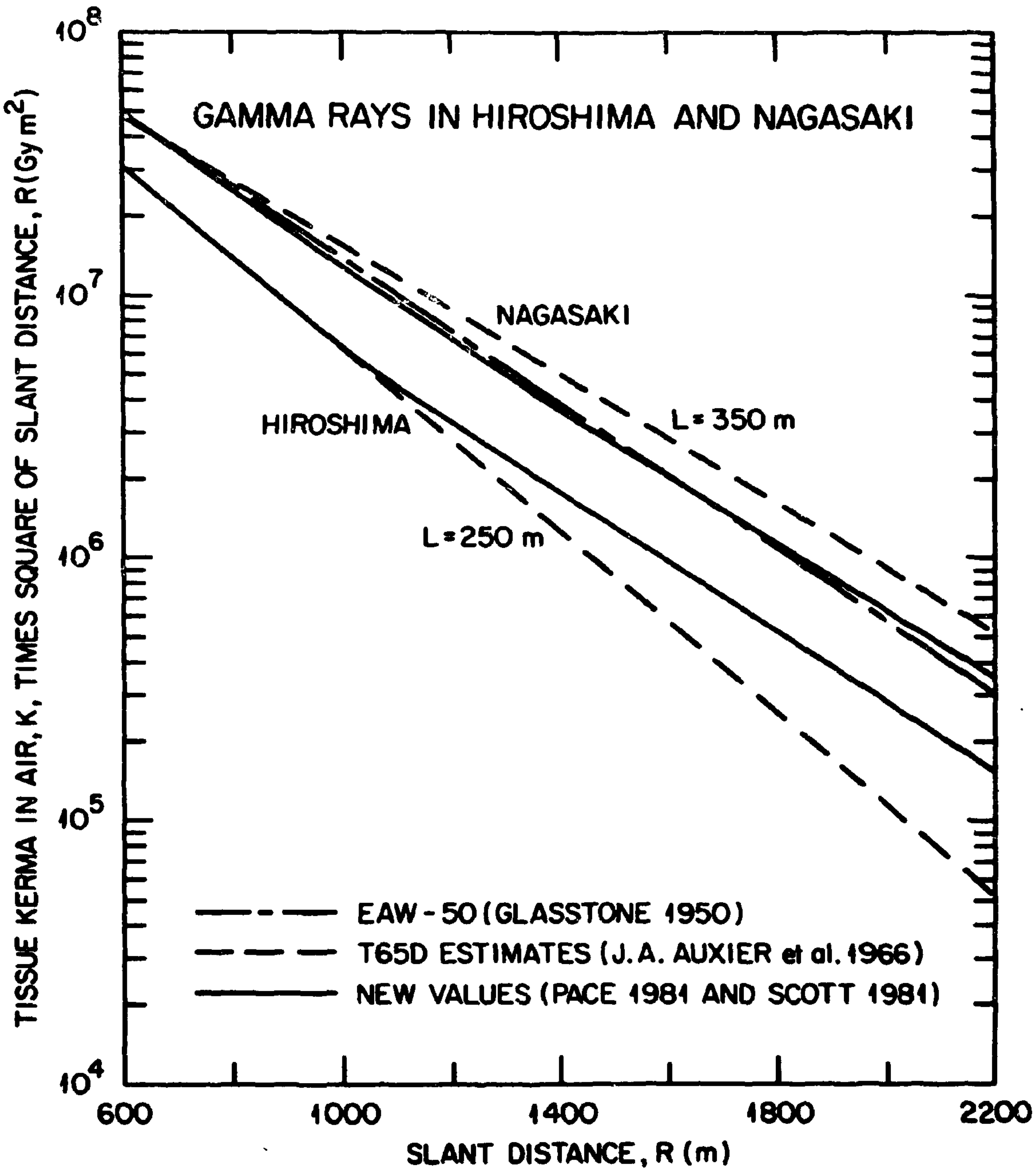


Fig. 21. Comparison of best state-of-the-art calculations and T65D estimates of the gamma-ray exposure in Hiroshima and Nagasaki as a function of ln $(KR^2)$ vs R, where K is tissue kerma in air and R is the slant distance from the burst point of the weapon.

Table 11. Summary of parameters from the T65D study (Auxier et al., 1966) and several previous studies of dosimetry for the atomic-bomb survivors (York, 1957; Wilson, 1956; Harris, 1955b)

| Parameter | Auxier et al. 1965 | York 1957 | Harris 1955 | Wilson[a] 1951 |
|---|---|---|---|---|
| **Hiroshima** | | | | |
| Energy yield, W (kton) | 12.5 | 18.5 | 18.5 | 20 |
| Height of burst, H (m) | 570 | 550 | 610 | 600 |
| Kerma relaxation length, L (m) | | | | |
| Neutrons | 198[b] | 218 | 201 | 196 |
| Gamma rays | 250[b] | 346 | 329 | 320 |
| Extrapolated source term, $G_0$ ($Gy\ m^2$)[c] | | | | |
| Neutrons | $8.70 \times 10^8$ | $8.64 \times 10^8$ | $1.12 \times 10^9$ | $7.66 \times 10^9$ |
| Gamma rays | $3.45 \times 10^8$ | $2.16 \times 10^8$ | $2.64 \times 10^8$ | $3.34 \times 10^8$ |
| **Nagasaki** | | | | |
| Energy yield, W (kton) | 22 | 23 | 23 | 20 |
| Height of burst, H (m) | 500 | 520 | 520 | 600 |
| Kerma relaxation length, L (m) | | | | |
| Neutrons | 198[b] | 218 | 201 | 196 |
| Gamma rays | 350[b] | 346 | 329 | 320 |
| Extrapolated source term, $G_0$ ($Gy\ m^2$)[c] | | | | |
| Neutrons | $1.30 \times 10^8$ | $1.25 \times 10^8$ | $1.64 \times 10^8$ | $5.65 \times 10^8$ |
| Gamma rays | $2.75 \times 10^8$ | $2.68 \times 10^8$ | $3.29 \times 10^8$ | $3.34 \times 10^8$ |

[a] Values of the extrapolated source term for neutrons are taken from Table 1 of Auxier et al. (1966).

[b] Normalized by Auxier et al. (1966) to an estimated atmospheric density of 1.13 kg $m^{-3}$ in both cities ATE.

[c] One Gy (or gray) unit is numerically equal to 100 rad units and to approximately 95 R or rep units used in some earlier reports.

spectrum of fast neutrons from Little Boy (see Fig. 20). The distance R from the burst point was nearly 2000 m before the spectrum of air transported neutrons reached an equilibrium state and the kerma relaxation length approached a constant value (J. Pace, 1981). At smaller distances R, the kerma relaxation length varied in magnitude, and the above equation was not applicable.

A constant kerma relaxation length for gamma rays in Hiroshima was also assumed in the T65D study by Auxier et al. (1966) (see Fig. 21) on the basis of data from (a) the Operation BREN studies using the HPRR and a $^{60}Co$ source to simulate the secondary and fireball gamma-ray fields of a weapon, respectively (Haywood et al., 1965), and (b) total gamma-field measurements made during several of the most nearly appropriate tests of modern fission weapons (i.e., nominal energy-yield weapons fired at about the same burst height as Little Boy) (Auxier et al., 1961). The HPRR or a modern fission weapon (i.e., a gun-assembly device with no HE, like Little Boy, or an implosion-type device with a thin HE system) produce very few thermalized neutrons compared with a Fat Man device with a thick HE system (Marcum, 1978). In the case of Fat Man, the copious number of "bomb" thermal neutrons (see Table 5) interact with nitrogen in the HE of the weapon and in the surrounding air to produce an intense "localized" source of high energy gamma rays (3 to 10 MeV). The secondary gamma rays are produced throughout a larger volume of air in the case of the HPRR, a modern fission weapon, or Little Boy. As pointed out by Auxier et al. (1966), the kerma relaxation length should be smaller in Hiroshima than in Nagasaki on the basis of geometry considerations alone. This appears to be the situation at smaller distances in Hiroshima, but at larger distances, the secondary gamma rays produced by the severely degraded energy spectrum of fast neutrons from Little Boy start to behave as a localized source (or point source), and the kerma relaxation length starts to resemble that of Fat Man in Nagasaki (see Fig. 21).

Finally, comparisons of the newer calculations of the gamma-ray exposure in Nagasaki have shown closer agreement with data from the Crossroads Able test (Glasstone, 1950) than with the T65D estimates

(Auxier et al., 1966) (see Fig. 21). The T65D tissue kerma vs distance relationship for gamma rays in Nagasaki was constructed from LANL film measurements made during the Ranger Fox test of a Fat Man implosion-type device in 1952 (Auxier, 1977; Storm, 1952). Simultaneous film measurements made during later weapons tests by the Evans Signal Depot and by LANL (Nuclear Development Corporation of America, 1957; Storm and Bemis, 1955) and laboratory studies by LANL (Storm and Bemis, 1955) indicated that their film measurements overestimated the gamma-ray exposure with the degree of overestimation varying with distance. This is a moot issue since the T65D values came from the test firing of a modified Fat Man implosion-type device with a tamper and core quite different from those in the Nagasaki weapon (Marcum, 1978; Malik, 1954), and it cannot be assumed, on the basis of present knowledge, that either the neutron or the gamma-ray output of these two devices was the same.

## DISCUSSION

Some findings of the review are that the neutron exposures in Hiroshima were probably less than the T65D estimates by factors varying from about four at a ground distance of 1000 m to eight at 2000 m (see Fig. 22), and the gamma-ray exposures were greater than the T65D estimates starting at a ground distance of about 1000 m and were probably larger by a factor of about three at 2000 m (see Fig. 22). In Nagasaki, the situation was reversed with respect to gamma rays, and the T65D estimates were higher (see Fig. 23), but the differences were small (i.e., about 20% at a ground distance of 1000 m and 30% at 2000 m). As a result, it now appears that leukemia and other late effects at lower exposure levels in Hiroshima were due largely to gamma rays rather than neutrons. This may not be true at higher exposure levels in Hiroshima, however.

If the newer radiation-exposure values shown in Figs. 22 and 23 are used (Kerr, 1981), then the correlation between leukemia in survivors of the two cities and absorbed dose to active marrow of the survivors is not as good as that obtained by Loewe and Mendelsohn (1980a). They

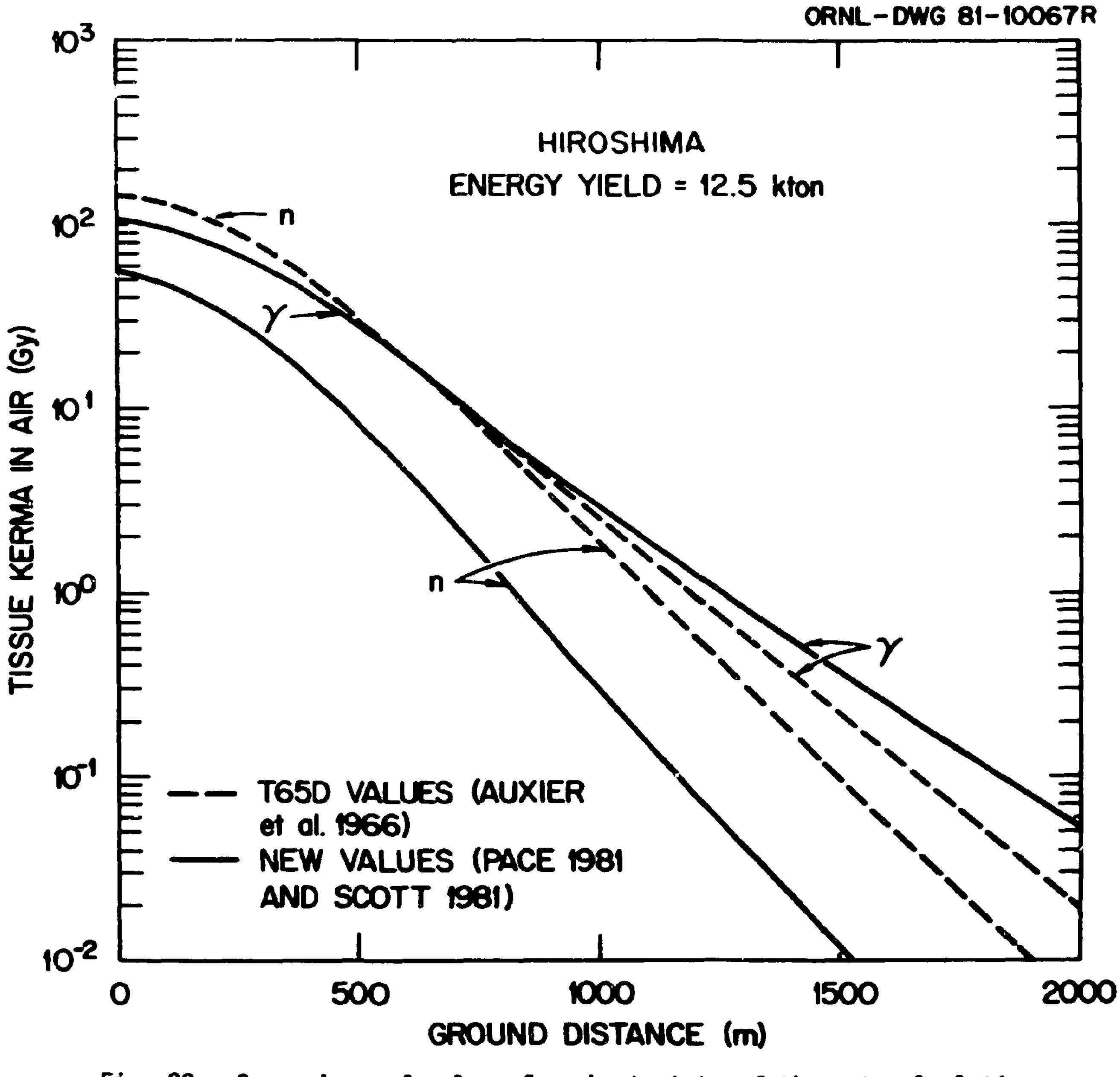


Fig. 22. Comparison of values from best state-of-the-art calculations and T65D estimates of the radiation exposure in Hiroshima.

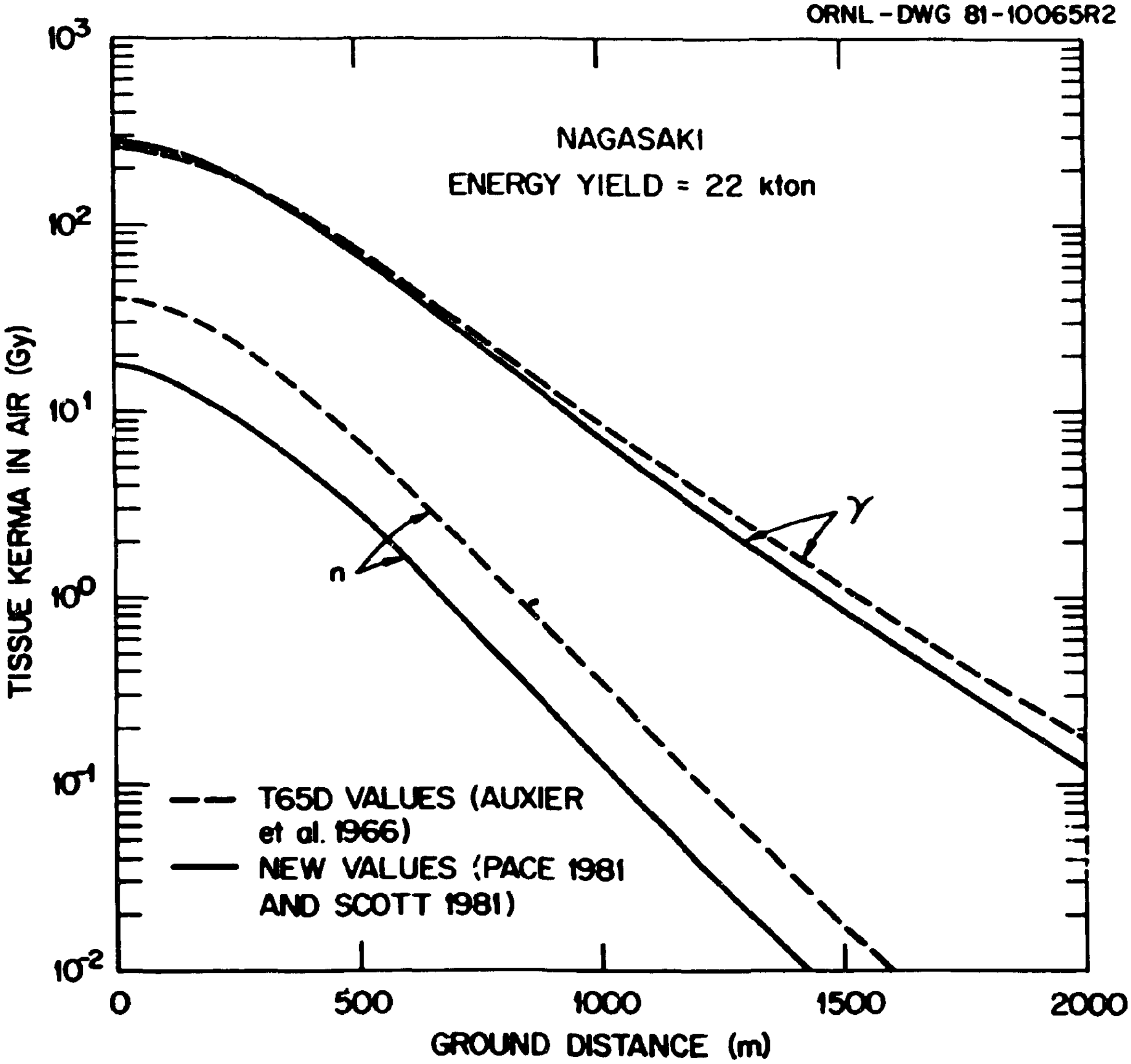


Fig. 23. Comparison of values from best state-of-the-art calculations and T65D estimates of the radiation exposure in Nagasaki.

attribute the leukemia at all exposure levels in the two cities to gamma rays. However, survival inside houses in Hiroshima started at about 700 m and reached 50% at about 900 m (Davis et al., 1966). At these, and even slightly larger, ground distances in Hiroshima, the neutron exposure inside houses is not negligible compared with the gamma-ray exposure if the RBE of neutrons for whole-body exposure is of the order of 10 (National Council on Radiation Protection, 1971a; 1971b). The results of any reanalysis of data on observed biological effects in the survivors should be regarded as highly speculative until some of the following issues have been investigated in more detail.

1. Organ-dose factors. The T65D estimates take into account a survivor's distance from ground zero and shielding by surrounding structures, but they do not consider the shielding of an organ of interest by overlying tissue of a survivor's body. Factors from studies by Jones (1977) and by Kerr (1979a) for converting the T65D estimates into an absorbed dose in an organ of a survivor must be updated using data from newer theoretical calculations of the energy and angular distributions of the neutron and gamma-ray fields in the open and inside a Japanese house. New techniques developed at ORNL for inserting mathematical models of the body into the MORSE radiation-transport code (Emmett, 1975) appear to provide the best calculational approach. Recent improvements in the mathematical models of the body (Cristy, 1980; 1981) and in the response function for the absorbed dose to active marrow (Kerr, 1980c) should also be used in updating the organ-dose factors.

2. Shielding factors for houses. The radiation exposure to survivors inside houses ATE has been estimated by using the nine-parameter formulas developed by Cheka et al. (1965). An investigation of a large number of actual house-shielding cases (see Fig. 5) by Milton and Shohoji (1968) indicated that typical shielding factors (or transmission factors) for gamma rays and neutrons were about 0.90 and 0.31 in Hiroshima and about 0.81 and 0.34 in Nagasaki. It has recently been suggested by Marcum (1981) of RDA that the house-shielding factors for gamma rays were probably more like 0.55 in Hiroshima and 0.50 in Nagasaki.

Adjoint MORSE calculations, which have been used in other shielding studies (Rhoades, 1974; Scott et al., 1975), are needed in updating the shielding factors for typical Japanese houses (Noble, 1968; United States Strategic Bombing Survey, 1947).

3. Energy yield of Little Boy. The energy yield used in the T65D study by Auxier et al. (1966) was 12.5 kton, and the probable error was later estimated to be about 1 kton (Auxier, 1975). It has recently been suggested by Malik (1980) of LANL that the energy yield of Little Boy was 15 (±3) kton. A probable error greater than 1 kton in the T65D value is indicated by Malik's review of data on distances for equal physical damage in the two cities (Auxier, 1977; Oak Ridge National Laboratory, 1968) and data on the air pressure record from parachute retarded canisters dropped by the observation aircraft (Auxier, 1977; Oak Ridge National Laboratory, 1968; Caudle, 1965), but his findings do not appear sufficient at present to warrant a change to 15 kton, since several other studies predict an energy yield more like the T65D value of 12.5 kton (Penney et al., 1970; Davis et al., 1963; Kimura et al., 1953). It appears necessary to collect and review all data related to the energy yield of the Little Boy device dropped in Hiroshima.

4. Neutron leakage from Little Boy. The gun-assembly device was cylindrically symmetric, and Preeg (1976) knew that the 1-D calculation was approximate, but he thought in view of time and effort constraints that it would suffice (Marcum, 1978). However, it is now apparent that a cylindrically symmetric mockup of Little Boy and a 2-D calculation are needed to establish the neutron exposure and neutron activation in Hiroshima more precisely.

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